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Telemetry Antenna for Lincoln Experimental Satellites LES-1 and LES-2

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

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Group 61

TECHNICAL REPORT 394

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ABSTRACT

The telemetry antenna used on the first two Lincoln Experimental Satellites consists of four short stubs equally spaced around, and parallel to, the spin axis of the satellite. A detailed description of the antenna and its transmission-line system is presented. Theoretical and model studies leading to the design of this antenna are discussed. Calculated and measured performance data are presented and compared.

Accepted for the Air Force
Stanley J. Wisniewski
Lt Colonel, USAF
Chief, Lincoln Laboratory Office

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TELEMETRY ANTENNA FOR LINCOLN EXPERIMENTAL SATELLITES LES-1 AND LES-2

I. INTRODUCTION

Major goals in the design and fabrication of the first Lincoln Experimental Satellite (LES) telemetry antenna were:

(a) Omnidirectional radiation patterns.

(b) Gain and efficiency high enough to provide more than the minimum effective radiated power required by the telemetry link.

(c) Minimum shadowing of the satellite's solar cells by the antenna elements.

(d) A mechanical configuration compatible with the launch package.

(e) Small-size and light-weight radiating elements, transmission lines, and impedance matching networks.

(f) Ability to withstand environmental extremes of temperature, radiation, acceleration, shock and vibration during launch and in orbit.

Several possible antenna configurations were considered, and some were tried experimentally before the present design was adopted. The size and shape of the satellite and its launch shroud imposed severe limitations on the types of antennas that could be used. Both slot and stub radiating elements were considered, slot elements being particularly attractive because, being flush, they would not shadow the solar panels. However, they occupy area which could be covered with solar cells; for this reason, small-diameter stub elements were chosen. Tested on the satellite were 1-, 2-, 4- and 6-element configurations at the VHF telemetry frequency. Following is a description of the geometry finally selected.

II. TELEMETRY ANTENNA

The antenna consists of four $\frac{1}{8}$-wavelength (λ) unipoles mounted on the lower corner of the triangular panels in the upper hemisphere of the satellite (Fig. 1). These elements are fed in phase rotation; that is, the phase of the excitation voltage to each element is delayed an amount equal to its angular displacement from a reference element. Delay is provided by a coaxial transmission-line feed harness inside the satellite. The coaxial line is the semi-rigid type with a helical-cut dielectric. Each line was measured electrically to accomplish the phasing; impedance transformers were inserted at the junction of the lines to each pair of antennas to maintain a constant impedance throughout the phasing network. Each 7-inch-long stub antenna element was matched to 50 ohms by placing a shorted shunt stub across the coaxial feed line. The polarization of the present 4-element system is invariant with rotation of the satellite because the radiators are placed symmetrically about, and parallel with, the spin axis of the satellite.

III. THEORETICAL STUDY

An investigation of radiating slotted spheres, for another application, was in progress during the development of the LES telemetry antenna. Since a small annular slot on a sphere was thought to be a good approximation to a short stub on a regular polyhedron, the mathematical model of the slotted sphere was used to calculate the telemetry antenna radiation characteristics. First, the radiation pattern of a single, small annular slot on an equivalent sphere was calculated. The geometry and coordinate system are shown in Fig. 2.

Radius (a) of the equivalent sphere is the mean of the maximum and minimum distance from the center of the 26-side polyhedron to its surface. A zonal slot is formed by the intersection of the sphere and the two cones defined by $\Theta_1 \pm \alpha$. Therefore, the slot width is 2α.

With uniform slot excitation, the radiation field is a function of Θ only. Relative field strength is given by[1]

$$E = \sum_{n=1}^{\infty} \frac{j^n(2n+1)\,ka}{4\alpha n(n+1)\,[ka h_n^{(2)}(ka)]'} \frac{dP_n(\cos\Theta)}{d\Theta} \int_{\Theta_1-\alpha}^{\Theta_1+\alpha} \frac{dP_n(\cos\Theta)}{d\Theta} \sin\Theta\, d\Theta \qquad (1)$$

where $h_n^{(2)}$ is the spherical Hankel function of the second kind; $[ka h_n^{(2)}(ka)]'$ is the first derivative of the product of this function and its argument, with respect to the argument; k is the phase constant $2\pi/\lambda$; $P_n(\cos\Theta)$ is the zero-degree associated Legendre function of the first kind; and $j = \sqrt{-1}$.

Equation (1) represents a solution to Maxwell's equations as a series of spherical harmonics. The method of derivation is due to Stratton and Chu[2] of M.I.T. Convergence of the series is rapid, and less than ten terms are needed for practical values of the relative field at any value of Θ. This field is, of course, constant with φ. In general, E is a complex quantity (having a real and an imaginary part) at each point in the space around the sphere, because the Hankel function is complex. Equation (1) was programmed for solution by the IBM 7094 computer.

Figure 3 is a plot of the relative magnitude of E vs Θ for a single small slot ($\Theta_1 = 5°$, $\alpha = 1°$) on a sphere (ka = 1.62) equivalent to a single stub on the polyhedron satellite body. For comparison, it is superimposed on a plot of the measured relative field of a single short stub on a test model of the satellite at 240 MHz. Agreement is excellent.

Figure 4 shows the calculated and measured radiation patterns of two elements which are on opposite sides of the sphere and the polyhedron, respectively. As before, the elements on the sphere are small annular slots, while those on the polyhedron are short stubs fed in phase opposition at 240 MHz. Agreement between the two patterns is good, with differences being attributed to imperfect excitation of the test model as evidenced by the asymmetrical measured pattern.

Results similar to those shown in Figs. 3 and 4 confirmed the validity of the assumptions on which the theoretical study was based. The investigation continued with the result that four equally spaced elements on a great circle of the sphere were found to be inadequate to meet the requirements, while six elements would be satisfactory. A computer program was formulated that would calculate the radiation pattern of any number of elements, equally spaced on a great circle of a sphere. This was combined with a random number program to introduce random errors in the phase and amplitude of the assumed excitation. These programs are presented in the Appendix.

Six elements, equally spaced on a great circle of a sphere for which ka = 1.62, were calculated to produce a radiation pattern omnidirectional to within ±0.3 db in the plane of the elements. The corresponding measured pattern was omnidirectional to within ±1.3 db. Again the difference was attributed to errors in excitation of the test model, but now this theory could be tested by introducing assumed limits to phase and amplitude errors into the computer program. This would then rapidly calculate patterns resulting from a random distribution of these errors. From several hundred patterns calculated this way, the average was found to be omnidirectional within the limits shown in Table I. Listed are the assumed limits in the standard deviation in phase and magnitude of the excitation voltages; the phase was considered to be off by no more than 10°, and the magnitude by no more than 20 percent. Opposite each set of error limits is the resulting range of departure from an omnidirectional pattern and the mean of the pattern.

TABLE I

RADIATION PATTERN CHARACTERISTICS AS A FUNCTION OF EXCITATION ERRORS

Standard Deviation		± Departure from Omnidirectional	
Phase (deg)	Magnitude (percent)	Range (db)	Mean (db)
10	20	1.0 to 4.5	3.3
10	0	0.7 to 3.0	2.0
0	20	1.6 to 3.3	2.5
0	10	0.8 to 1.8	1.3

A magnitude error of 10 percent is quite likely, since the voltage-standing-wave ratio (VSWR) measured at a typical element is about 1.1 after careful adjustment of the matching network. Similarly, phase errors are likely to be quite small, for transmission line lengths were measured and equalized electrically. Therefore, the last case listed in Table I is most likely, and the mean departure from omnidirectional does correspond with the measured value.

The foregoing was cited mainly to show the usefulness of this type computer program. It can be used either to determine the effect of random errors or to establish tolerances for particular parameters. To do this experimentally would be impractical because of the time and labor required to make all the incremental changes and to measure the results.

Each element of the proposed 6-element antenna would be limited in length to $1\frac{1}{2}$ inches because of mechanical interference considerations. The wavelength is about 50 inches, and a $1\frac{1}{2}$-inch stub is too short (relative to the wavelength) to be an efficient radiator. Such a short element would be very difficult to feed, since the required impedance matching network would be lossy, narrow band, and sensitive to environmental changes.

The chance of mechanical interference would be reduced and the elements could be made longer by moving them close to the top of the satellite. Since they would also be closer to one another, fewer elements might be satisfactory. The computer program was modified to permit calculation of radiation patterns when the elements were not located on a great circle of the sphere but on a circle of any latitude.

When calculating patterns in a plane other than that containing the radiating elements, the orthogonally polarized field components must be determined at each point of observation. Thus, for the chosen spherical coordinate system, the component field in the Θ direction (E_Θ) and that in the φ direction (E_φ) would be the logical choice. These components are readily found from Eq. (1) by a transformation of the coordinate system which allows an element to be located anywhere on the sphere instead of being limited to the position shown in Fig. 2.

Geometry of the transformation is shown in Fig. 5. Note that Θ', which is measured from the center of the annular-slot element to any point $P(\Theta, \varphi)$, corresponds to Θ in Eq. (1). This change in notation permits use of the unprimed coordinate (Θ) in the new, transformed coordinate system which applies to the more general case where the slot can be located anywhere on the sphere. The coordinates of the center of the slot are Θ_c and φ_c, as indicated in Fig. 5. From this figure, the following equations are obtained by spherical trigonometry.

$$\Theta' = \arccos\left[\cos\Theta_c \cos\Theta + \sin\Theta_c \sin\Theta \cos(\varphi_c - \varphi)\right] \tag{2}$$

$$\psi = \arcsin \frac{\sin\Theta_c \sin(\varphi_c - \varphi)}{\sin\Theta'} \tag{3}$$

or

$$\psi = \arccos \frac{\cos\Theta_c - \cos\Theta \cos\Theta'}{\sin\Theta \sin\Theta'} \quad . \tag{4}$$

Having found the angle ψ from Eqs. (3) or (4), we may split the known relative field $E(\Theta')$ from Eq. (1) into orthogonal components; thus,

$$E(\Theta, \varphi) = (i_\Theta \cos\psi \pm i_\varphi \sin\psi)\, E(\Theta') \tag{5}$$

where $0 \leqslant \Theta' \leqslant 180°$ and i is the unit vector. When $180° < \varphi_c - \varphi < 360°$, use the plus sign; when $0° < \varphi_c - \varphi < 180°$, use the minus sign. For the special case of $\varphi_c = \varphi$,

$$E(\Theta, \varphi) = E(\Theta') \qquad \text{when } \Theta > \Theta_c \tag{6}$$

$$E(\Theta, \varphi) = -E(\Theta') \qquad \text{when } \Theta < \Theta_c \quad . \tag{7}$$

Equations (2) and (4) through (7) were programmed for the computer (see Appendix). Equation (4) is preferred over Eq. (3) for the computer, since it gives unambiguous principal values of the angle ψ. This modified program permits calculation of the relative field at any point in the space around a sphere, with any number of radiators located anywhere on the sphere and fed with voltages of any phase and magnitude. It was made general for possible future use on other array configurations.

The configuration considered most practical for LES telemetry application, at this time, was the 4-element array finally adopted and described in Sec. II above. Four small annular slots, equally spaced around a sphere with $ka = 1.62$ and $\Theta_c = 64.5°$, constitute the equivalent antenna. One of the elements is taken to be the reference element at $\varphi = 0$; the elements are fed in phase rotation, with the excitation voltage to each delayed an amount equal to the element's φ-coordinate.

In general, the resultant field is elliptically polarized; but, with perfect excitation, it is circularly polarized at $\Theta = 0°$ and $180°$. Basically, the configuration is analogous to a turnstile antenna. However, the performance is modified by the conducting sphere which is equivalent to the polyhedron satellite body.

In the equatorial plane ($\Theta = 90°$), the principal polarization (E_Θ as a function of φ) calculates to be omnidirectional to within ±0.6 db. $E_\varphi(\varphi)$ is not so omnidirectional, deviating by ±4.3 db. Patterns presented in Figs. 6(a) through (q) were calculated and plotted by the computer for constant values of Θ in 10° steps from 10° through 170°. On Fig. 6(a) is a sketch defining the coordinate system; Fig. 6(i) is the plot for the equatorial plane ($\Theta = 90°$) from which the values cited previously were taken. At $\Theta = 0°$ and 180°, orthogonal field components are equal in magnitude and constant with φ.

In addition to the magnitudes, the computer gives the phase of each component at each calculated point so that the resultant field can be found, if desired. Since the intention is to use linearly polarized receiving antennas at the ground telemetry terminal, variation of the linearly polarized components around the spin axis of the satellite is important. "Conical-cut" patterns, such as those presented in Figs. 6(a) through (q), indicate the variation that can be expected in the signal received by horizontally and vertically polarized antennas at any viewing angle as the satellite spins on its axis. Patterns are rotationally symmetric and repeat every 90° in φ; therefore, only one quadrant is presented in each figure. Reference level is the maximum which occurs at $\Theta = 180°$, as shown by patterns calculated in planes of constant φ. These pattern cuts, through the spin axis, are shown in Figs. 7(a) through (c). Patterns in Fig. 7(a) are typical of the radiation in planes containing two elements and the spin axis, while those in Fig. 7(b) are for $\varphi = 45°$, the plane exactly between two elements. Minimum E_Θ does not occur in this plane, however, but in the $\varphi = 35°$ plane at $\Theta = 80°$ [see Fig. 6(h)]. Patterns are shown for $\varphi = 35°$ in Fig. 7(c) as they emphasize an interesting phenomenon. As careful examination of the conical pattern cuts reveals [Figs. 6(a) through (q)], radiation is not symmetrical about the planes containing the antenna elements. Therefore, in general, maxima of E_Θ do not occur in the planes of the elements and minima do not occur in the planes exactly between elements, as might be expected.

Radiation pattern information is summarized in Figs. 8 and 9 for use in estimating the effect of radiation characteristics on the performance of the telemetry link. Figure 8 is the ratio between the maximum and the minimum field, for each polarization, as a function of Θ. If, for example, the angle between the ground station and the spin axis is 80°, Fig. 8 shows that E_φ would vary as much as 9.1 db as the satellite rotates about its axis, while E_Θ would vary less than 1.6 db. Figure 9 shows that the average power level would be about −6.5 db for E_φ and −4.2 db for E_Θ, with the field at $\Theta = 180°$ as the reference. Actually, Fig. 9 gives the average of maximum and minimum fields which (in db) is close to the average power level since the variation is almost sinusoidal. In the practical telemetry circuit, the variation observed would depend also on the method of detection.

Sufficient information is contained in the patterns to calculate the approximate directivity of the antenna by point-to-point integration. Thus, the maximum pattern directivity over isotropic for each field (E_φ or E_Θ) is given by

$$D = \frac{E_{max}^2 \ \Sigma \sin\Theta}{\Sigma \ E^2 \sin\Theta} \tag{8}$$

with the summation carried out over all of the area around the antenna for which the patterns were calculated, taking advantage of symmetry to reduce the number of points. The equation

is an approximation because a finite number of points are used; the larger the number of points and the closer together they are, the more accurate the value for the directivity. E_{max} is the magnitude of the largest field at any point in the pattern. For a pattern normalized to the maximum, it becomes unity, of course. E is the magnitude of either the φ or Θ field (depending on the field for which the directivity is being calculated) at each point (Θ, φ).

The computer was programmed (see Appendix) to store all the field information and use it to solve Eq. (8) for the maximum directivity at the reference ($\Theta = 180°$). For E_Θ, directivity is 3.86 times that of an isotropic antenna; for E_φ, it is 2.54. As stated before, this is the radiation-pattern directivity which is a function only of the shape of each three-dimensional radiation field. At $\Theta = 180°$, the resultant ideal field is known to be circularly polarized, as computed values of E_Θ and E_φ are equal in magnitude and in phase quadrature. This means that the power must be divided between the two fields in inverse proportions to their directivities, and the directivity of each linearly polarized component field is given by

$$D_L = \frac{D_\Theta D_\varphi}{D_\Theta + D_\varphi} \quad . \tag{9}$$

For the specific case under consideration,

$$D_L = \frac{3.86\ (2.54)}{3.86 + 2.54} = 1.53 = 1.84\ \text{db}$$

and the directivity of the resultant circularly polarized field is twice that of each component, or 4.85 db.

The gain of the test model antenna was measured at $\Theta = 90°$ and $\varphi = -17°$, as this was a more convenient reference for the test setup than $\Theta = 180°$. Translating this to $\Theta = 180°$ by means of measured radiation patterns, the gain to linear polarization is found to be about 2 db above isotropic for one field and 1 db below isotropic for the orthogonal field. (Due to imperfect excitation, the experimental field is not circularly polarized.) From this, the gain of the resultant elliptically polarized field is calculated to be 3.76 db. Since the difference between directivity and gain is the loss in the antenna radiators and transmission-line system, this loss calculates to be about 4.84 − 3.76 db = 1.08 db, which is reasonable.

With the theoretical maximum directivity of each linearly polarized component field now known, the directivity at any point in space can be read, or interpolated, from the patterns shown in Figs. 6 and 7. Adding 1.84 db to any value found from these plots gives the directivity over isotropic at that point.

IV. MODEL STUDY

As indicated in Sec. III above, the first design consisted of six elements on a great circle through the satellite. The elements were restricted to $1\frac{1}{2}$ inches in length in order not to shadow the solar panels. This system accomplished the desired result in that there was radiation at all angles from the satellite in some polarization; however, the system had two basic faults. First, the polarization varied as the satellite was rotated about the spin axis, i.e., at 180 rpm, while the ground station finally chosen consisted of two linearly polarized receiving antennas either one of which, but not both, could be receiving at the same time. Second, and greater, the impedance matching device on the antenna could not maintain a match over the temperature changes of its environment. The theoretical impedance and some measured data for various

length antennas[3] are shown in Fig. 10. The calculated VSWR of the $1\frac{1}{2}$-inch stub is about 2000:1, but the antenna was matched using a shorted shunted stub approximately 6 inches from the feed point. However, the positioning of this device was so critical that a 50°F change in temperature resulted in a change in VSWR from 1.0 to 1.5. The antenna must work over at least a 100°F range; therefore, the longer antenna shown in Fig. 1 was tested. Its input impedance is approximately 9–j104 ohms and the corresponding VSWR is about 70:1. This impedance was reduced to 50 ohms by inserting a tee in the coaxial line (Fig. 11) with an adjustable short circuit on one arm. The VSWR of each antenna was reduced to approximately 1.1:1. It was physically impossible to measure the impedance of one antenna with the other antennas excited, but the input VSWR of the feed harness terminated in the four matched elements is about 1.15:1 (average of five harnesses).

This feed harness was composed of electrically measured lengths of coaxial line and impedance transformers (Fig. 12) so that there was a successive 90° delay between the four stubs and a roughly 50-ohm impedance at the input. Since the phase delay was inserted by varying cable length, it was necessary to find a coaxial line which would retain phase stability over a large temperature range. This line would naturally change phase with temperature; however, it should not change electrical length permanently. Two types of cable were temperature cycled: RG-188/U, a Teflon-insulated flexible cable; and a 0.161 semi-rigid coaxial line with a helical cut irradiated polyolifin dielectric. These cables were alternated between liquid nitrogen and boiling water five times, and the Teflon cable was found to have changed electrical length permanently by approximately 2 percent while the helical cut dielectric cable change was unmeasurable.

TM connectors were chosen because they mechanically clamp to the semi-rigid coaxial cable. This design permitted the use of aluminum connectors, thus reducing weight. The weight of the entire harness and antennas is $3\frac{1}{4}$ ounces. At each tee, a section of 35-ohm coaxial transmission line was inserted to match the junction to 50 ohms. This cable was of the same design as the 50-ohm cable except for inner-conductor size. The 50-ohm connectors were used on this 35-ohm line. Each transformer was measured and cut electrically so that it and the tee, and two 50-ohm loads, presented an input VSWR of 1.05 or less. Each cable electrical length was also measured in an attempt to keep the misphasing under 2° or about $\frac{1}{2}$ cm in cable.

Antenna patterns were measured using a sheet-metal model of the satellite with the stub antennas mounted on the triangular panels and the feed harness inside. The test model was then mounted about 9 feet above the ground on an approximately $8 \times 3 \times 1$-foot styrofoam pillar (Fig. 13). A single cable was run down the center of the pillar through a rotary joint to the receiver. Antenna patterns were measured using two orthogonal linearly polarized transmitted signals (vertical and horizontal). The satellite and transmitter were placed outside over relatively flat ground. At this frequency there are problems with reflections which must be tolerated as no anechoic chamber is available. Tests were made to determine the effect of the reflections by changing the distance between the transmitter and receiver in increments of 1 foot for about 5 steps (i.e., from 26 to 30 feet). The depth of nulls was affected but, generally speaking, the basic patterns did not change for either polarization. Most of the patterns were taken with the satellite in the position shown in Fig. 13; that is, the satellite was rotated in a constant Θ-plane, varying φ. A typical pattern is shown in Fig. 14. For the conical cuts, the transmitting antenna was elevated and the satellite was in the position shown in Fig. 13, then rotated 180° on the styrofoam resulting in two cuts equi-angle from the equator. These are shown in Figs. 15(a)

through (f). Several patterns were taken varying Θ, with φ held constant. It is almost impossible to physically mount the satellite in those positions corresponding to the theoretical patterns. This, in part, can explain the difference in results obtained.

Three flight models of the LES were moved to the Antenna Test Range for pattern and effective radiated power measurements (Fig. 3). The telemetry transmitter was operating ($\approx$500-mw output) and the signal was received on two orthogonal linear polarizations. Figure 14 shows the effective radiated power and equatorial pattern of the LES-2 package. The gain calculated from this measurement is about 0.6 db below isotropic at $\Theta = 90°$. The measurements on the other flight items provided approximately the same results with gain at $\Theta = 90°$ near isotropic.

On 11 February 1965, the first satellite (LES-1) was launched from Cape Kennedy. It went into a circular parking orbit with the third stage of the Titan III A launch vehicle, as planned. A rocket package, which was supposed to inject the satellite into an elliptical orbit, failed to fire and to separate itself from the satellite. Therefore, the satellite with the injection package attached is apparently tumbling as well as spinning about its axis. This seems evident from the nature of the signals received. Indications are that the telemetry antenna survived the launch and is operating as expected, even though the radiation characteristics are altered by the presence of the injection package.

On 6 May 1965, LES-2 was launched from Cape Kennedy on a Titan III A and this time it went into the planned elliptical orbit. All systems are operating, and performance of the telemetry antenna is satisfactory.

V. CONCLUSIONS

A practical VHF telemetry antenna has been developed for the Lincoln Experimental Satellite. It consists of four short-stub antenna elements mounted on triangular panels of the satellite and fed in phase rotation. All the performance criteria were met, and operation in the space environment is satisfactory.

There is reasonable agreement between theoretical and measured radiation characteristics. These show that, at any point in space around the satellite, the effective radiated power in one of two orthogonal linearly polarized fields is always large enough to be utilized by the ground station, which employs a polarization diversity antenna system.

Theoretically, maximum signal occurs at $\Theta = 180°$ where the field is circularly polarized. Directivity, at this coordinate, was computed to be 4.84 db. Model measurements confirm that maximum field occurs off the bottom of the satellite, but the field is elliptically polarized because of imperfect excitation of the antenna elements. Gain, to matched polarization, was calculated (from measured data) to be 3.76 db. The difference, 1.08 db, is attributed to losses in the elements and in the transmission-line system.

All components were designed to survive the environmental extremes imposed by the launch into orbit, and to operate in space. After thorough testing on the ground, two satellites were placed in orbit where satisfactory operation has proven the design.

ACKNOWLEDGMENT

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REFERENCES

1. Y. Mushiake and R. E. Webster, "Radiation Characteristics with Power Gain for Slots on a Sphere," Contract DA 36-039 SC 42548, Ohio State University Research Foundation, Columbus, Ohio (15 August 1955).
2. J. A. Stratton and L. J. Chu, "Steady-State Solutions of Electromagnetic Field Problems," J. Appl. Phys. 12, 230 (1941).
3. C. W. Harrison, Jr., "Monopole with Inductive Loading," SCR-590, Sandia Corporation (November 1962).

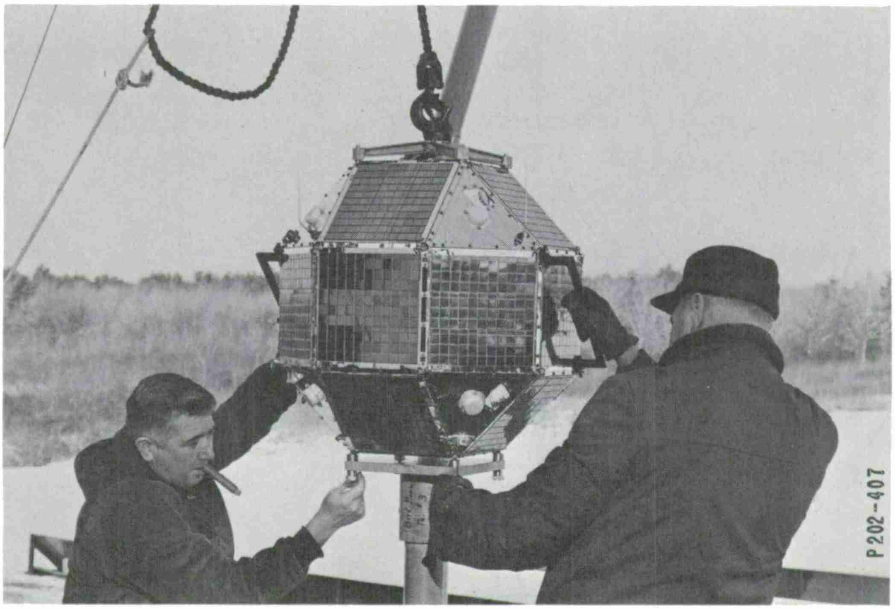


Fig. 1. First Lincoln Experimental Satellite.

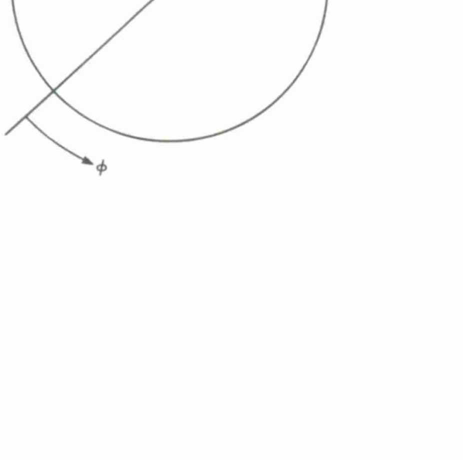


Fig. 2. Slotted-sphere geometry and coordinate system.

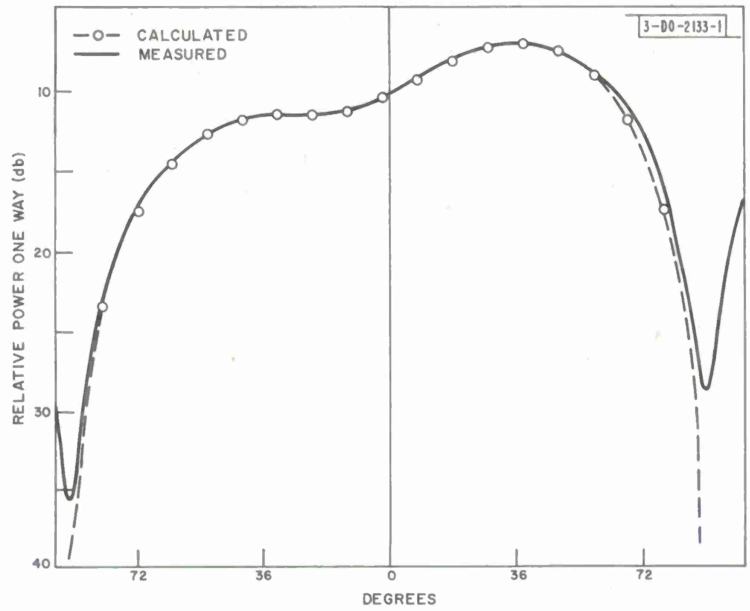


Fig. 3. Calculated relative field of single small annular slot on an equivalent sphere, and measured relative field of single short stub on 26-side polyhedron.

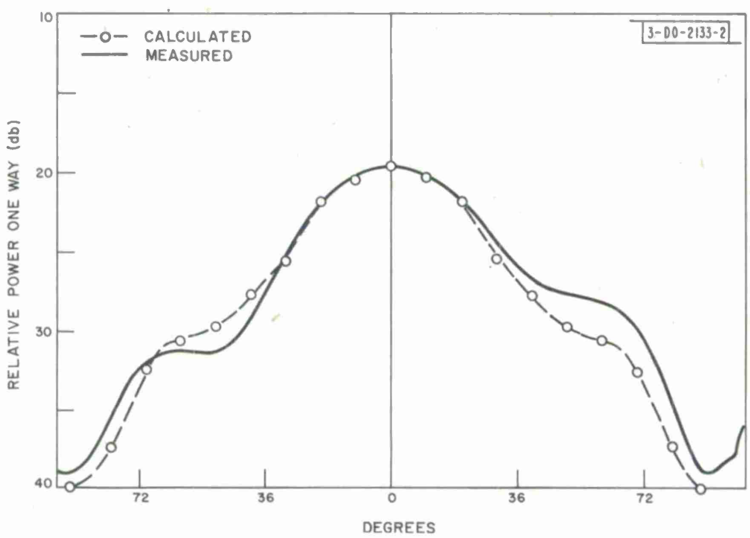


Fig. 4. Calculated and measured radiation patterns of two elements in space and phase opposition.

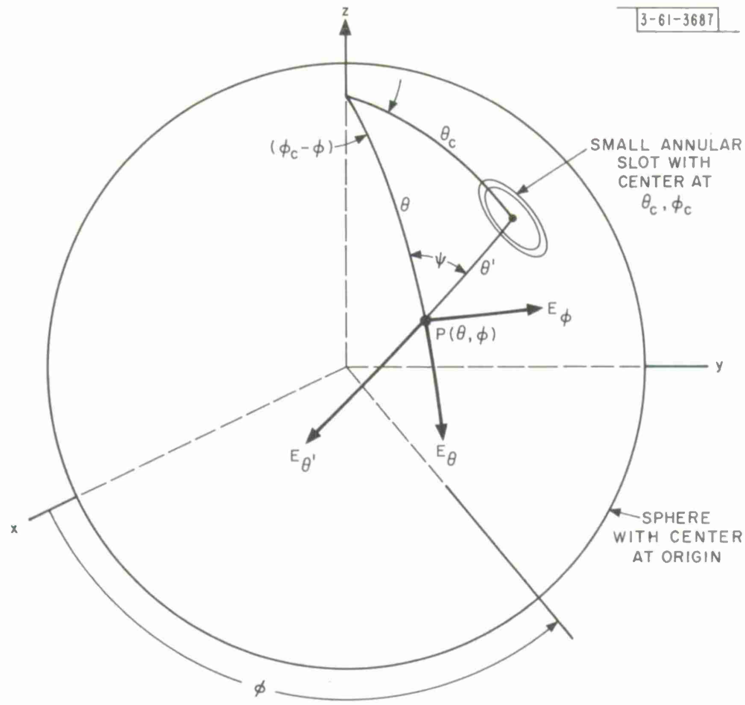
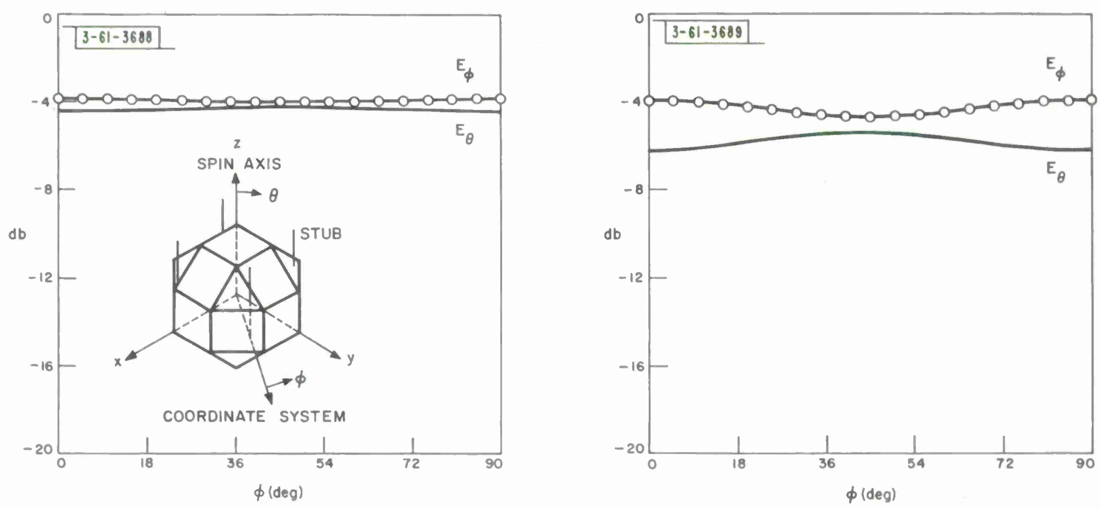


Fig. 5. Transformation geometry.

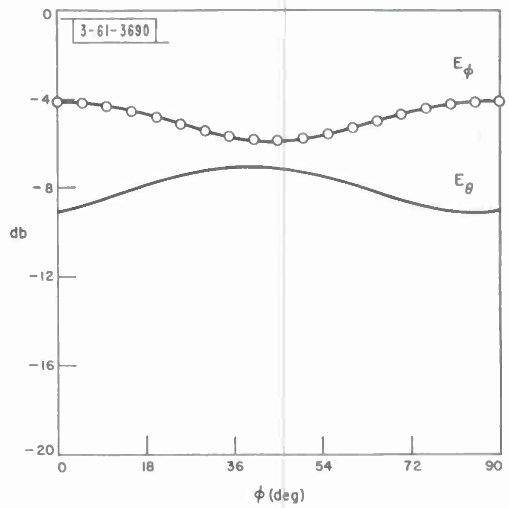


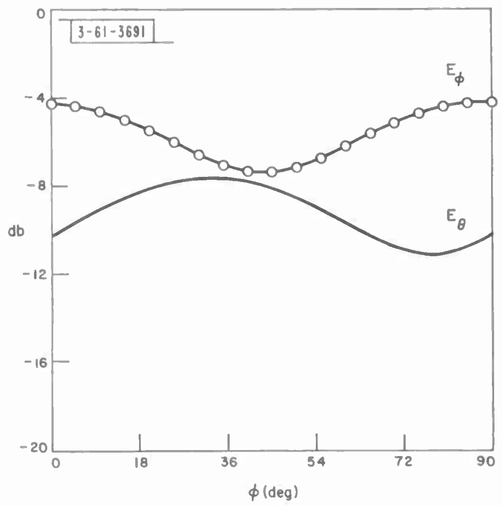
(a) $\theta = 10°$.

(b) $\theta = 20°$.

Fig. 6. LES telemetry antenna, calculated radiation patterns as a function of ϕ.

(c) θ = 30°.





(d) θ = 40°.

(e) θ = 50°.

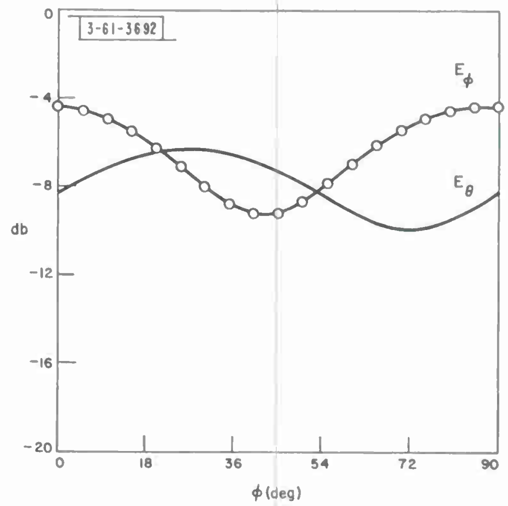
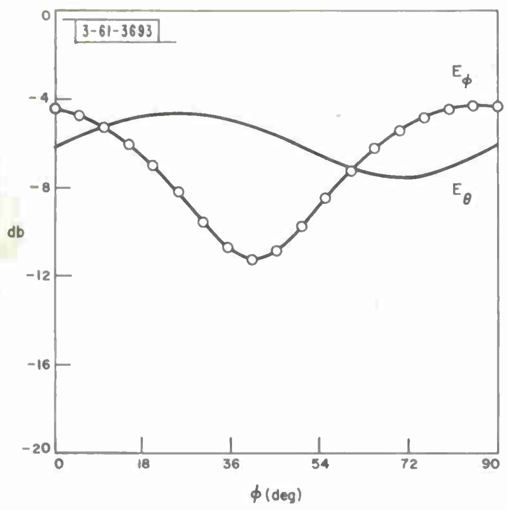
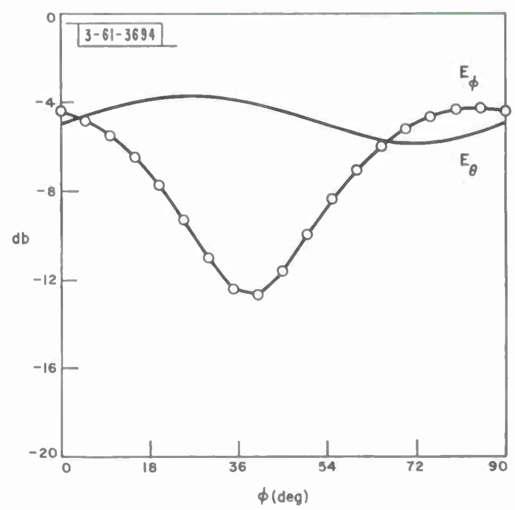


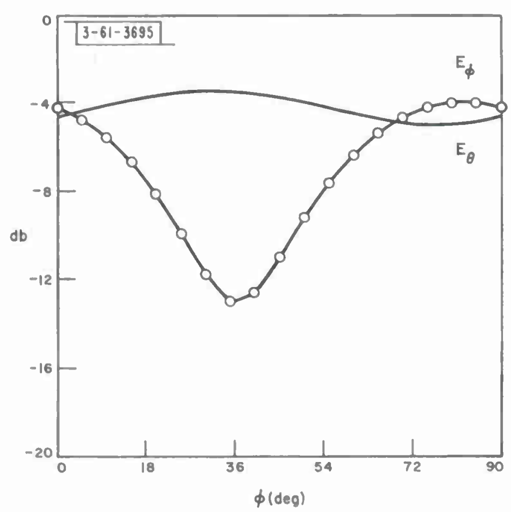
Fig. 6. Continued.



(f) θ = 60°.



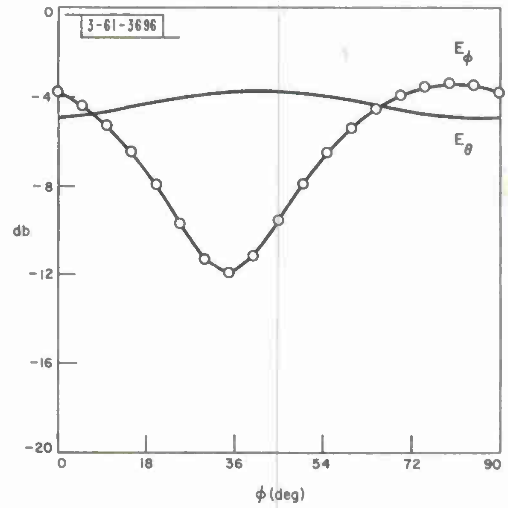
(g) θ = 70°.

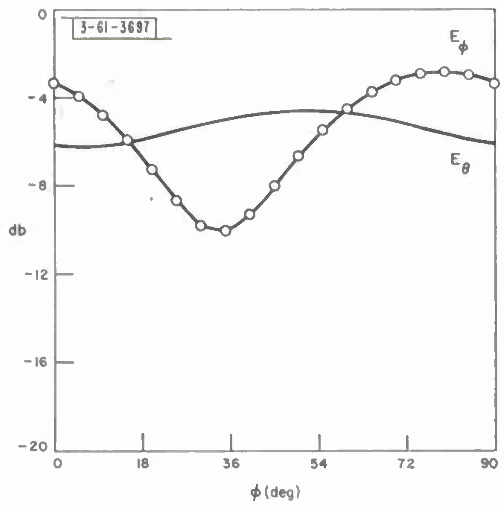


(h) θ = 80°.

Fig. 6. Continued.

(i) θ = 90°.





(j) θ = 100°.

(k) θ = 110°.

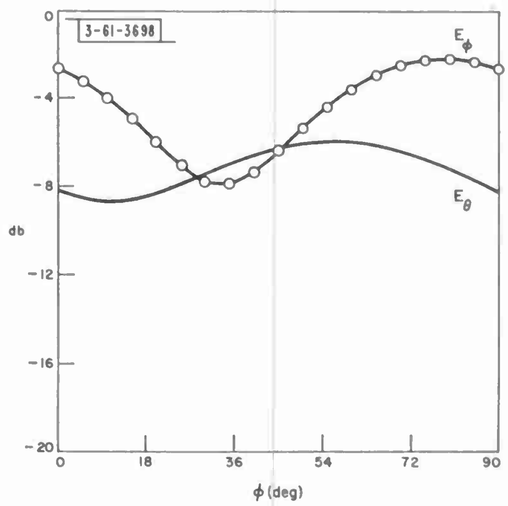
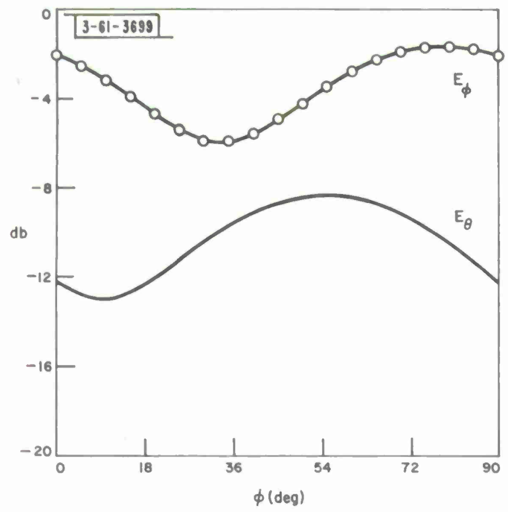
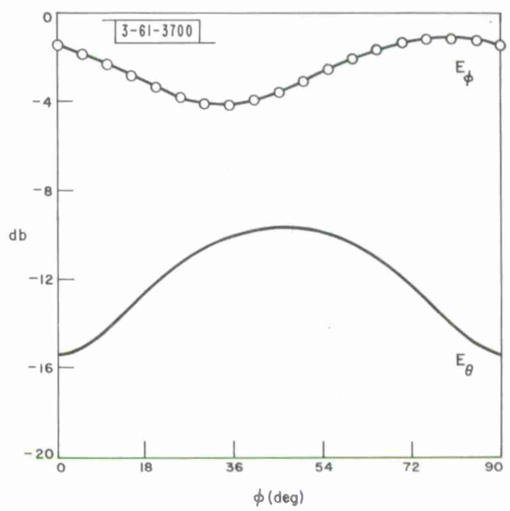


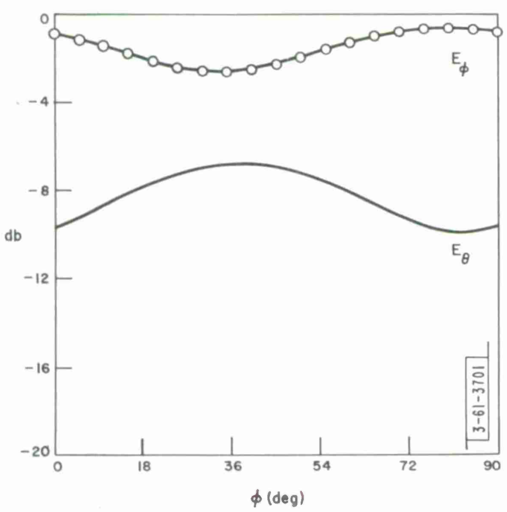
Fig. 6. Continued.



(l) θ = 120°.



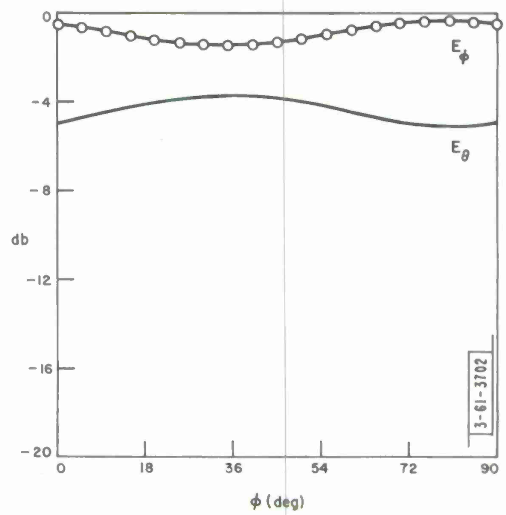
(m) θ = 130°.

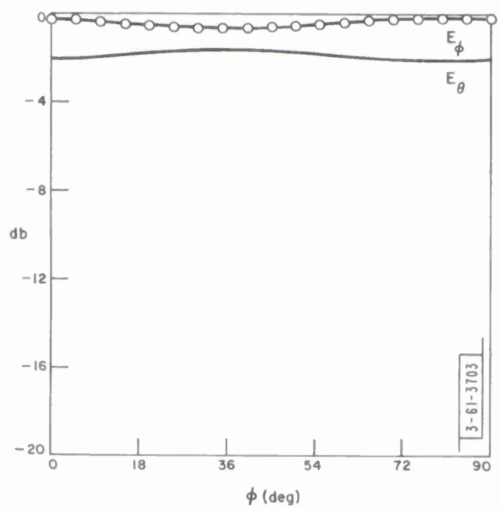


(n) θ = 140°.

Fig. 6. Continued.

(o) θ = 150°.





(p) θ = 160°.

(q) θ = 170°.

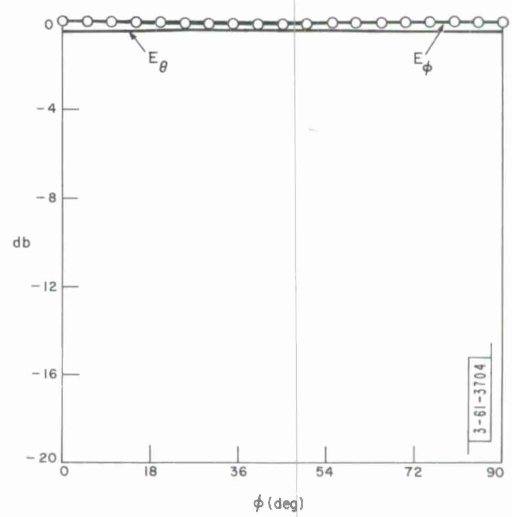
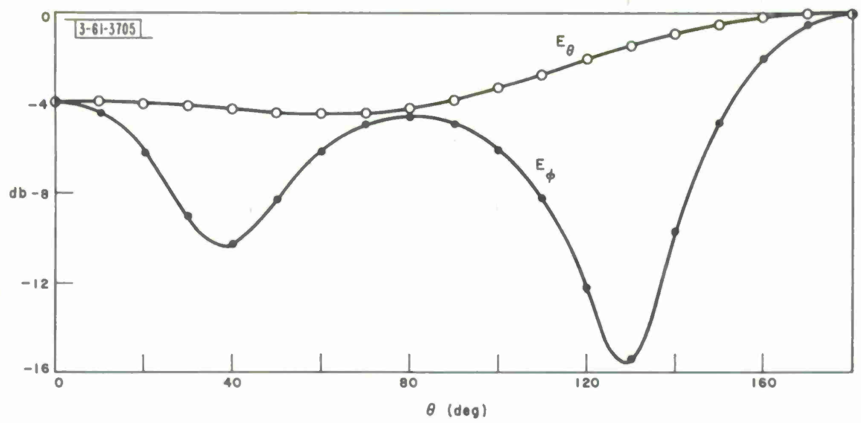
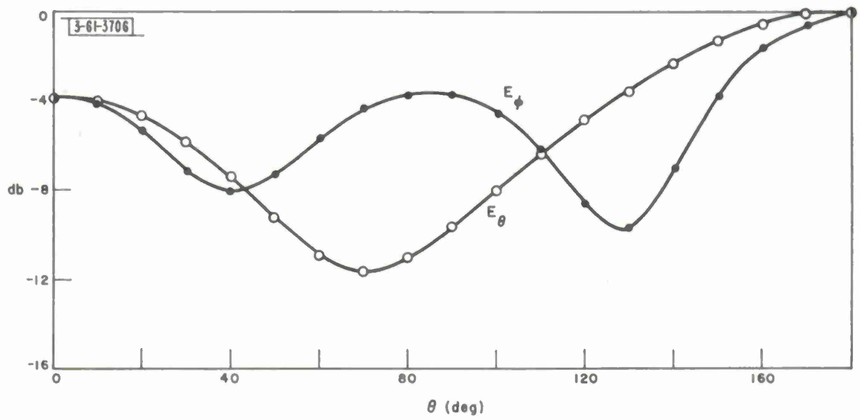


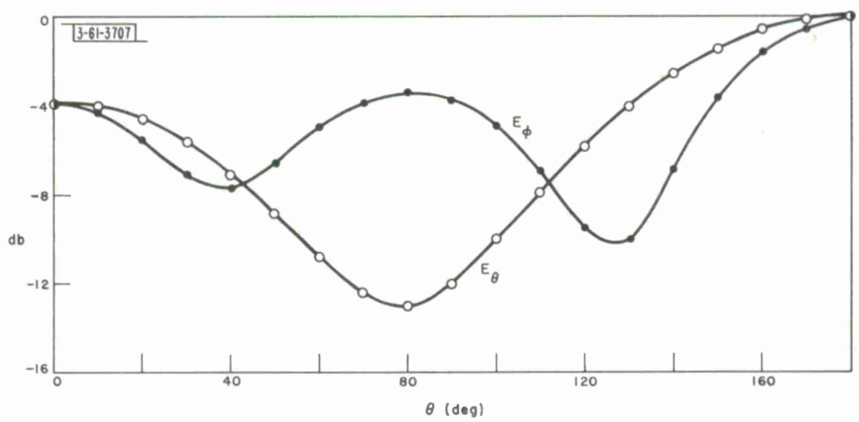
Fig. 6. Continued.



(a) $\phi = 0°$.



(b) $\phi = 45°$.



(c) $\phi = 35°$.

Fig. 7. LES telemetry antenna, calculated radiation patterns as a function of θ.

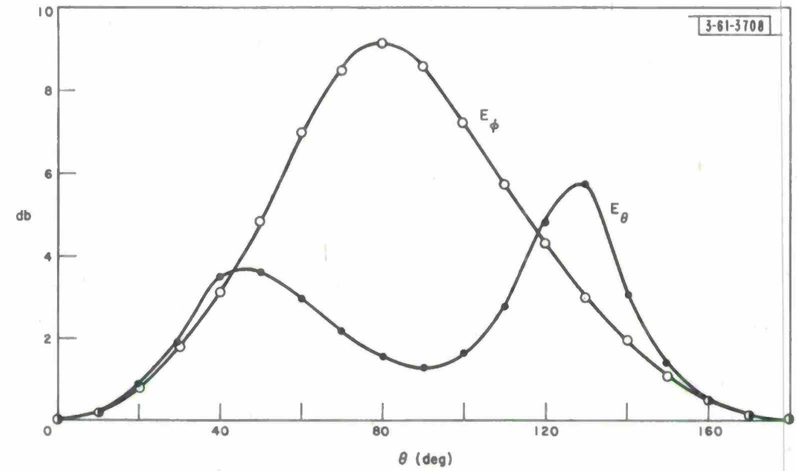


Fig. 8. Ratio of maximum to minimum field.

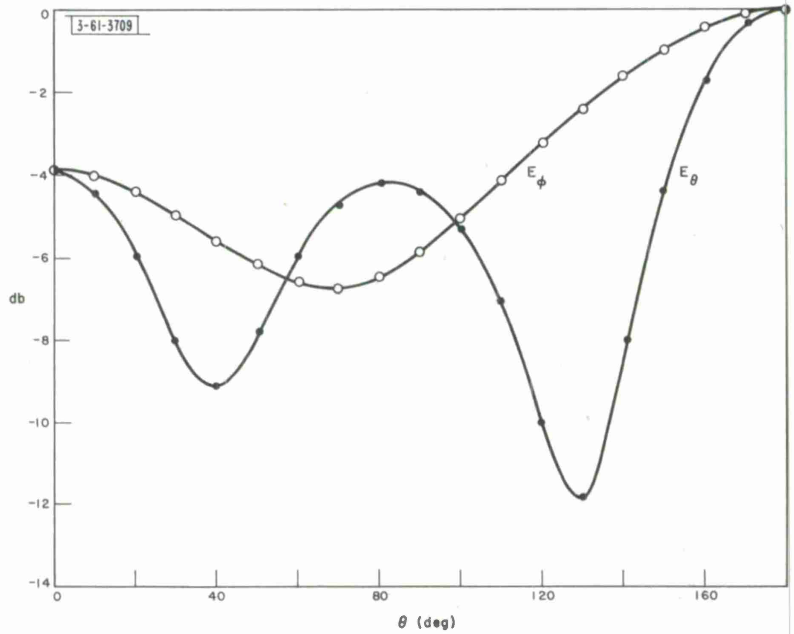


Fig. 9. Average of maximum and minimum field.

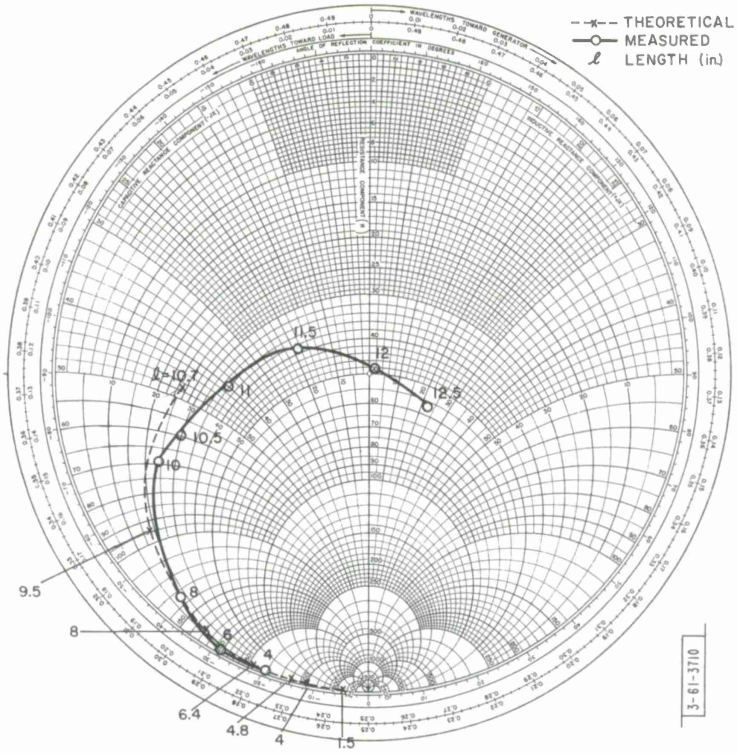


Fig. 10. Theoretical and measured impedance of a single monopole, varying length.

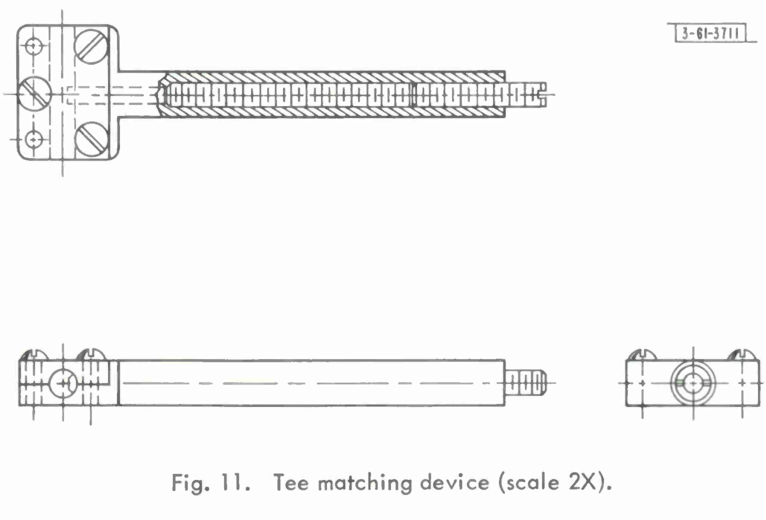


Fig. 11. Tee matching device (scale 2X).

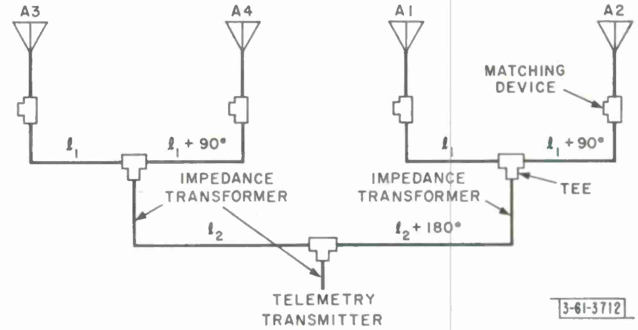


Fig. 12. Schematic of feed harness.

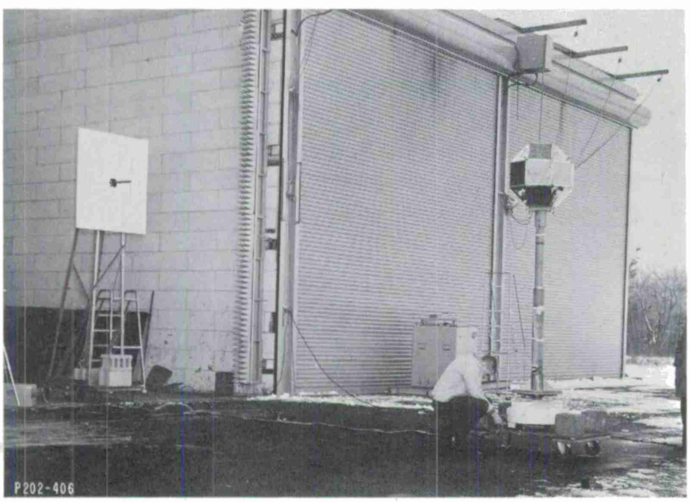


Fig. 13. LES mounted for antenna pattern measurement.

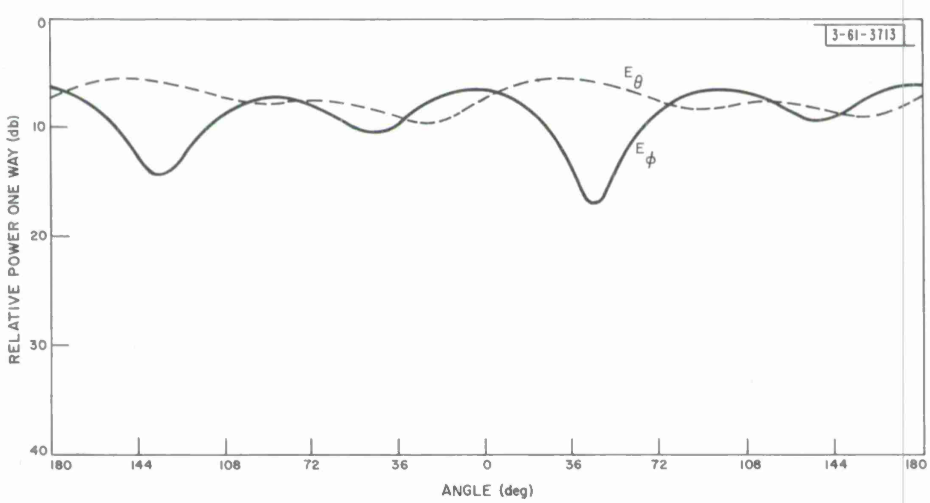
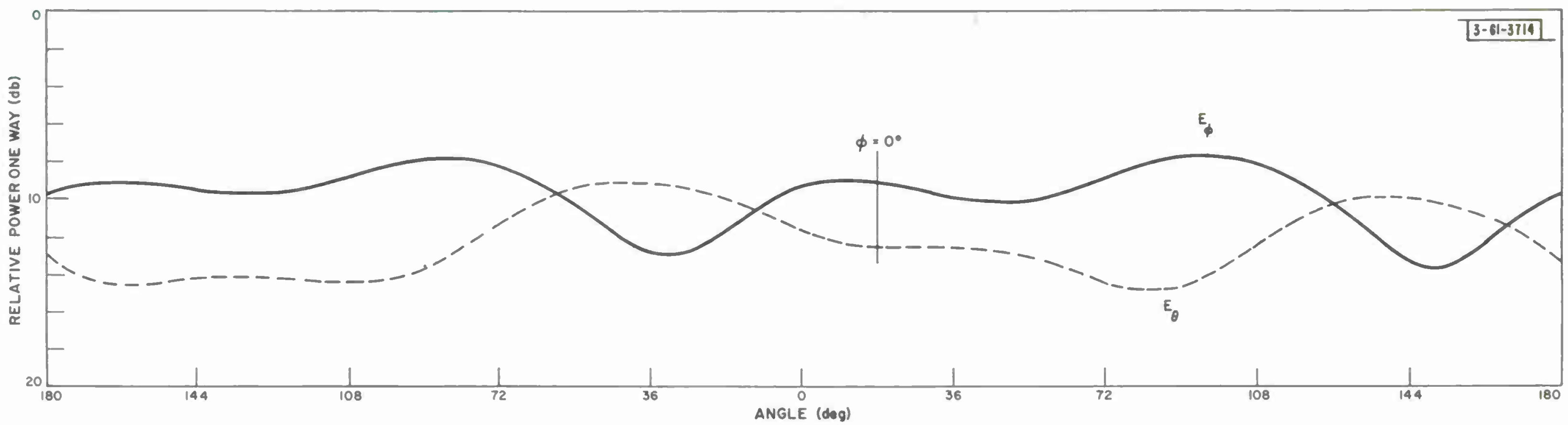
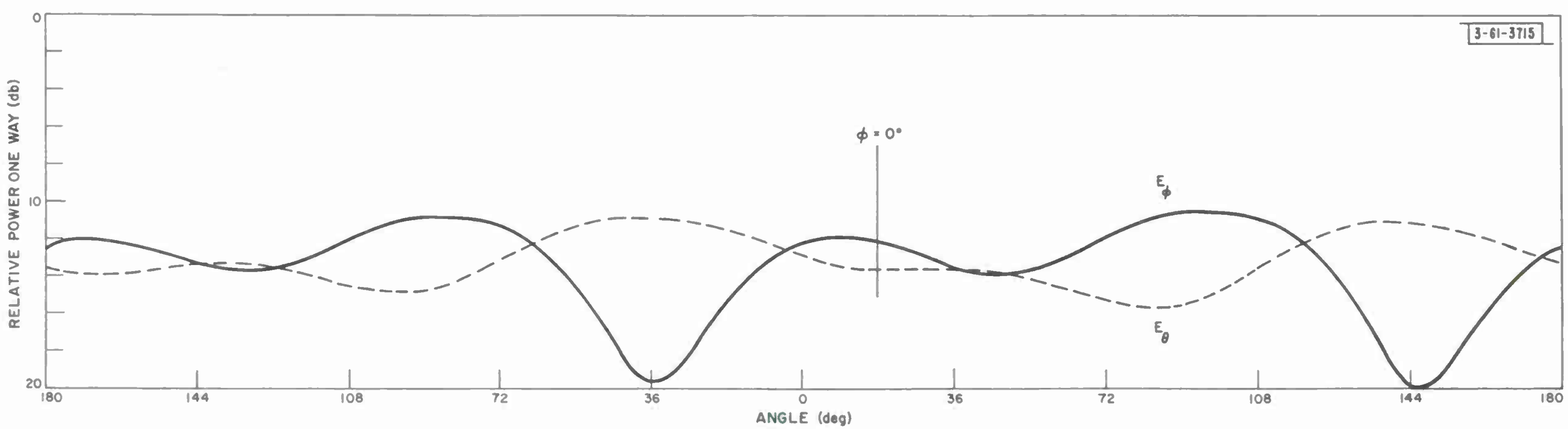


Fig. 14. Typical equatorial plane antenna pattern.

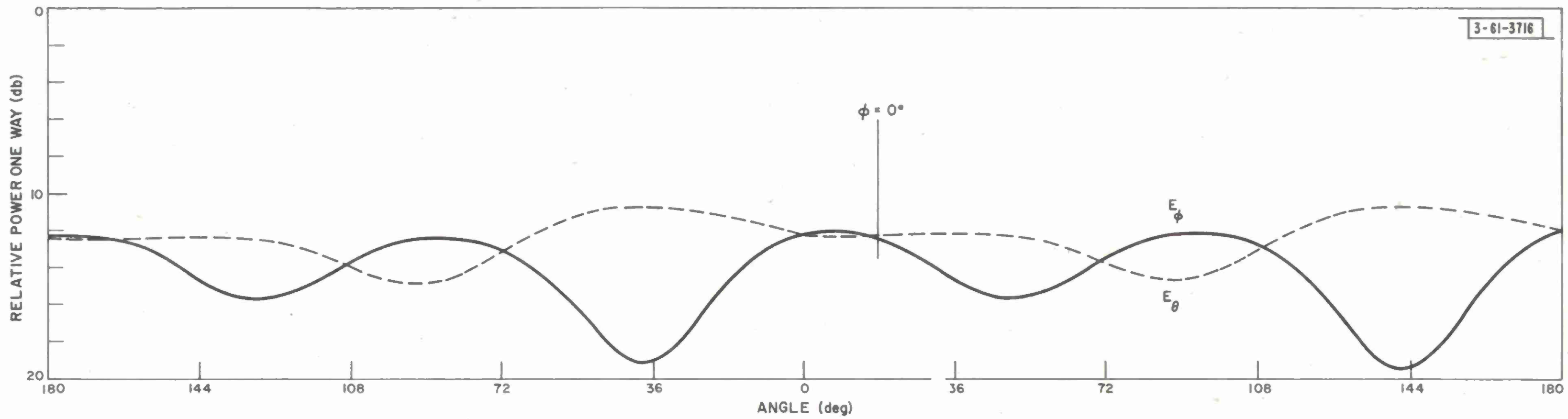


(a) θ = 50°.

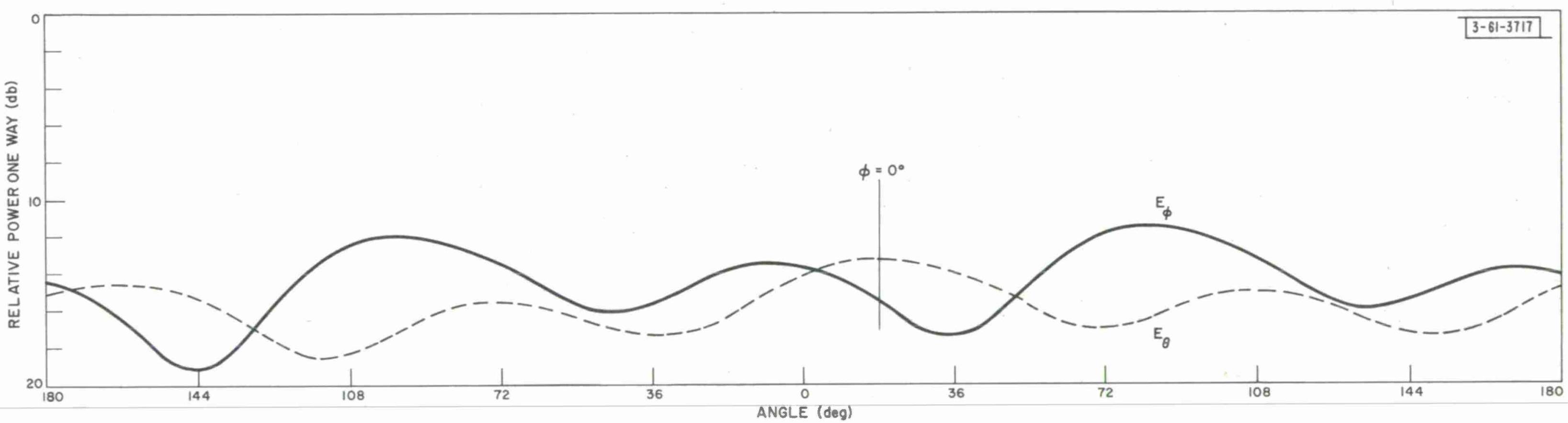


(b) θ = 60°.

Fig. 15. Antenna patterns as a function of φ for various values of θ.

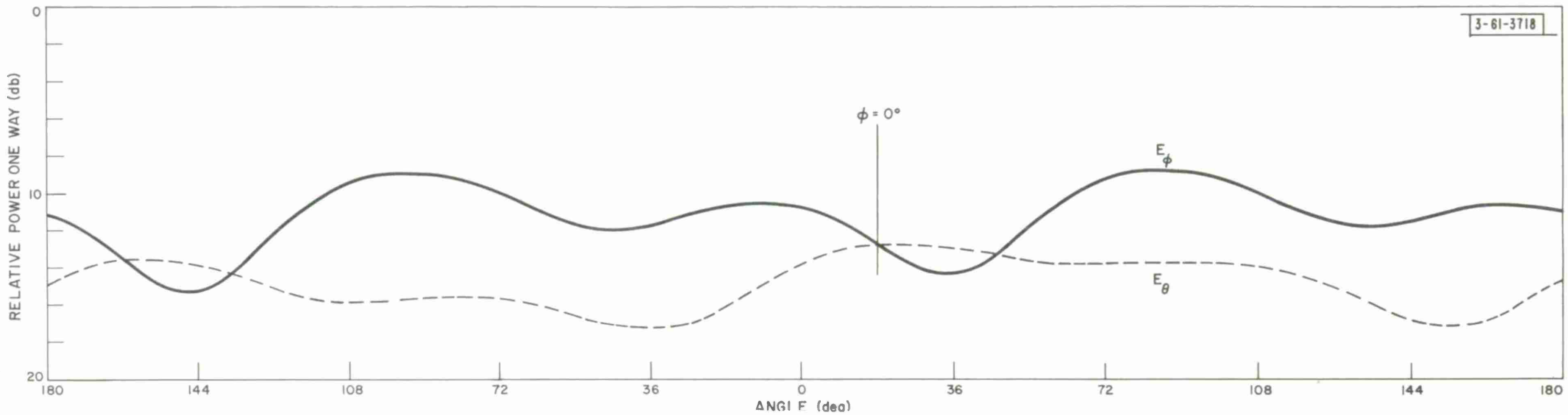


(c) θ = 70°.

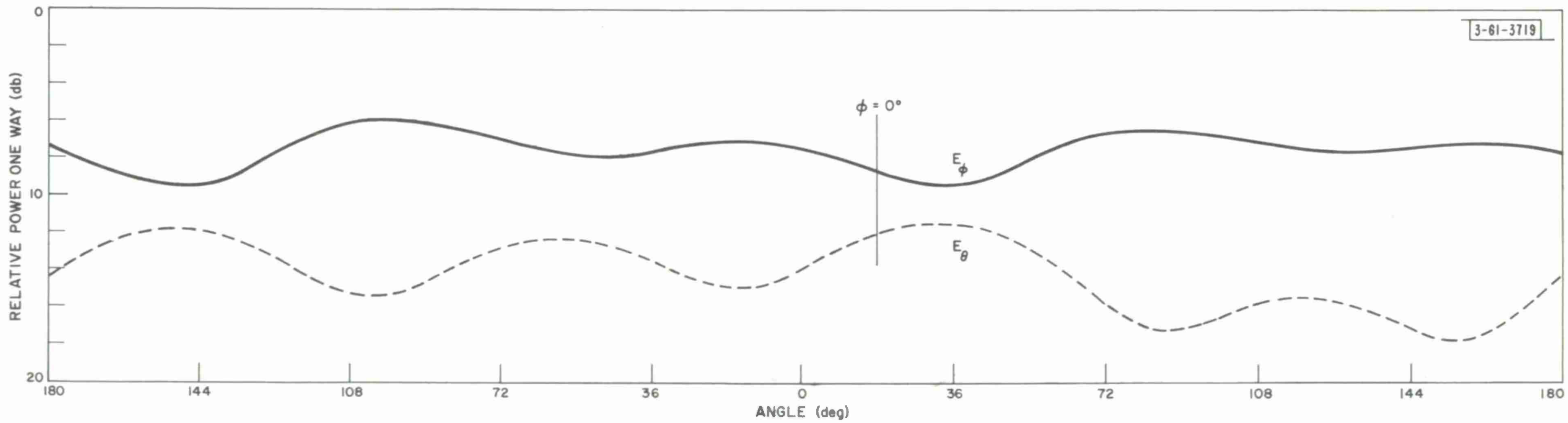


(d) θ = 110°.

Fig. 15. Continued.



(e) $\theta = 120°$.



(f) $\theta = 130°$.

Fig. 15. Continued.

APPENDIX
COMPUTER PROGRAMS

TABLE A-I

ELEMENT RADIATION FIELD

```
C         E FOR THETA = 0 - 180 DEG. - CALC. REAL +J(IMAG),VMAG,PHASE,DB
C              INPUT .. ARG,THETA1,ALPHA,DTHETA,NL,THZ,DTH,NTH
C        ARG = KA.....POSITIVE, LESS THAN 50. , REAL ONLY
C        THETA1 = ANG. POSITIVE, DEGREES
C        ALPHA = ANG.. POSITIVE, DEGREES
C        DTHETA = INTERVAL OF 2 PT. GAUSS INTEGRAL
C        NL = N LIMIT. POSITIVE INTERGER,=,LESS THAN 100
C        THZ = ANG. IN FAR-FIELD, DEGREES
C        DTH = ANG. INTERVAL OF FAR-FIELD ANGLE
C        NTH = NO. OF POINTS IN PATTERN
C
C              OUTPUT .. THETA,REAL,GAMI,MAGNITUDE,PHASE,VOLT. NORM.,DB
C        OUTPUT ON A-5 WILL BE PUNCHED (HOLLERITH). DATA WILL BE USED FOR
C           PROGRAM  THAT CALCULATES X NO. OF RADIATORS ON A SPHERE.
         DIMENSION THTBL(181),PI(2),SMREAL(181),SMIMAG(181),VLMAG(181),
        1PHASE(181),VLNORM(181),VLDB(181),HEAD(12)
C
C              TABLE OF CONSTANTS
B        PI(1) = 202622077325
B        PI(2) = 147042055061
         C1 = PI/180.
C        ------
C              READ IN HEADING CARD
      10 READ INPUT TAPE 2,1,(HEAD(I),I=1,12)
C              READ IN CONSTANTS FOR EACH CASE (ARG,THETA1,ALPHA,NL)
         READ INPUT TAPE 2,2,ARG,THETA1,ALPHA,NL
C              READ IN DTHETA,(THZ,DTH,NTH)
         READ INPUT TAPE 2,2,DTHETA,THZ,DTH,NTH
C
         WRITE OUTPUT TAPE 3,1,(HEAD(I),I=1,12)
         WRITE OUTPUT TAPE 3,3,ARG,THETA1,ALPHA,NL
         WRITE OUTPUT TAPE 3,4,DTHETA,THZ,DTH,NTH
C        ------
C              LOOP FOR FAR-FIELD ANGLE, THETA
         THETA = THZ
         DO 28 J=1,NTH
         THTBL(J) = THETA
C              LOOP TO CALCULATE SUMMATION,N=1,NL
         SUMRE = 0.
         SUMIM =0.
         DO 16 N=1,NL
C              LOOP TO CALC. BSUBN(THETA1,ALPHA,DTHETA,N,BNANS)
         CALL BSUBN(THETA1,ALPHA,DTHETA,N,BNANS)
         BSUBNA = BNANS
         ALPHAR = C1*ALPHA
         BND2AR = BSUBNA/(2.*ALPHAR)
C              CALC. 1ST DERIVITIVE OF X*H(2)SUB N*(X)
         CALL DDXHAN(ARG,N,REAL,GAMI)
C              CALC. D/DTH PSUB N(COS THETA)
         CALL DPNCOS(THETA,N,ANS)
         DPNANS = ANS
C
         ABA = ARG*BND2AR*DPNANS
         DEN = REAL**2+GAMI**2
         ABADEN = ABA/DEN
```

TABLE A-I (Continued)

```
C          TEST FOR VALUE OF (J)EXP N
      NN = XMODF(N,4) + 1
      GO TO (11,12,13,14),NN
C          NUMERATOR IS REAL,POSITIVE
   11 TRMRE = REAL*ABADEN
      TRMIM = -GAMI*ABADEN
      GO TO 15
C          NUMERATOR IS IMAGINARY,POSITIVE
   12 TRMRE = GAMI*ABADEN
      TRMIM = REAL*ABADEN
      GO TO 15
C          NUMERATOR IS REAL,NEGATIVE
   13 TRMRE = -REAL*ABADEN
      TRMIM = GAMI*ABADEN
      GO TO 15
C          NUMERATOR IS IMAGINARY,NEGATIVE
   14 TRMRE = -GAMI*ABADEN
      TRMIM = -REAL*ABADEN
   15 SUMRE = SUMRE+TRMRE
      WRITE OUTPUT TAPE 3,5,THETA,N,TRMRE,TRMIM
   16 SUMIM = SUMIM+TRMIM
      SMREAL(J) = SUMRE
      SMIMAG(J) = SUMIM
C          FIND VOLT. MAGNITUDE AND NORMALIZE TO MAXIMUM VALUE
C          CALCULATE PHASE ANGLE AND DB VALUE
      VLMAG(J) = SQRTF(SUMRE**2+SUMIM**2)
C          CALC. PHASE ANGLE -PI/2 TO 3PI/2
      PHASE(J) = ATANF(SUMIM/SUMRE)
      IF(SUMRE)21,24,28
   21 IF(SUMIM)22,23,22
   22 PHASE(J) = PHASE(J)+PI
      GO TO 28
   23 PHASE(J) = PI
      GO TO 28
   24 IF(SUMIM)25,26,27
   25 PHASE(J) = - PI/2.
      GO TO 28
   26 PHASE(J) = 0.
      GO TO 28
   27 PHASE(J) = PI/2.
   28 THETA = THETA+DTH
C          FIND MAXIMUM VALUE OF VLMAG
      VLMAX = VLMAG(1)
      DO 30 J=2,NTH
      IF(VLMAX-VLMAG(J))29,29,30
   29 JMAX = J
      VLMAX = VLMAG(J)
   30 CONTINUE
C          NORMALIZE VLMAG VALUES TO VLMAX AND CALC. DB VALUES
      DO 31 J=1,NTH
      PHASE(J) = PHASE(J)/C1
      VLNORM(J) = VLMAG(J)/VLMAX
   31 VLDB(J) = 20.*LOG10F(VLNORM(J))
C          WRITE OUTPUT VALUES
      WRITE OUTPUT TAPE 3,6,(THTBL(J),SMREAL(J),SMIMAG(J),VLMAG(J),PHASE
     1(J),VLNORM(J),VLDB(J),J=1,NTH)
      END FILE 3
      WRITE OUTPUT TAPE 5,7,(THTBL(J),SMREAL(J),SMIMAG(J),VLMAG(J),PHASE
     1(J),J=1,NTH)
      END FILE 5
      CALL EXIT
```

TABLE A-I (Continued)

```
C          FORMAT STATEMENTS
    1 FORMAT(12A6)
    2 FORMAT (3F10.6,I3)
    3 FORMAT (55H0INPUT VALUES -ARGUMENT     THETA 1     ALPHA   N LIMIT
     1/1H+60X58HDTHETA     THETA 0       DTH    NO. OF POINTS IN FAR-FIE
     2LD//1H 12XF8.4,5XF7.2,5XF6.2,6XI2)
    4 FORMAT (1H+60XF5.2,5XF7.2,6XF6.2,12XI3////1H020X43HLISTING OF THE
     1TERMS IN THE SUMMATION FOR E    //1H05X5HTHETA4X1HN5X9HREAL TERM6X
     214HIMAGINARY TERM)
    5 FORMAT (1H0F11.2,I5,2E16.6)
    6 FORMAT (95H1 THETA-DEG.   SUM OF REAL      SUM OF IMAG      VOLT.-M
     2AG.     PHASE   VOLT. NORMALIZED      DB//(F10.2,3E16.6,F10.2,E17.
     36,F10.2))
    7 FORMAT (F10.5,3E16.6,F10.5)
      END
```

TABLE A-II

RADIATION FIELD OF ANY NUMBER OF ELEMENTS
ON A GREAT CIRCLE OF A SPHERE

```
C MR2SEP64  TOTAL RADIATION PATTERN FOR ANY NO. OF RADIATORS ON A SPHERE
C     *******************************************************************
C     INCLUDE FPNDRN AND INNDRN SUBROUTINE
C
C      THE(I) = THETA (DEGREES)
C      ER(I)  = SUM OF REAL
C      EI(I)  = SUM OF IMAGINARY
C      VOL(I) = MAGNITUDE (VOLTAGE)
C      PH(I)  = PHASE (DEGREES)
C      PHI(J) = PHASE CORRECTION (DEGREES)
C      TH(J)  = ANGLE TO DETERMIN CORRECT EXCITATION VOLTAGE
C      STD    = STANDARD DEVIATION FOR RANDOM PHASE (DEG.)
C      STDV = STANDARD DEVIATION FOR VOLTAGE MAGNITUDE
C      INITRN = INITIAL NUMBER TO START RANDOM NUMBER ROUTINE
C         IF 0 OR -  ,  NO RANDOM NUMBERS IN PHASE OR VOLTAGE
C      ICONT  = CONTROL CARD FOR RANDOM NUMBERS. -1 * RANDOM PHASE,  0
C                 RANDOM VOLTAGE MAGNITUDE, +1 * RANDOM PHASE AND VOLTAGE
C      NTOTAL = TOTAL NUMBER OF PATTERNS PER SET OF STD , STDV OR BOTH
C      NEXC   = TOTAL NO. OF EXCITORS ON A SPHERE MINUS 1
C
       DIMENSION THE(50),ER(50),EI(50),VOL(50),PH(50),PHI(10),TH(10),EV(5
      10),EN(50),EDB(50),PHAS(50),SURE(50),SUIM(50),AN(10),RANV(10),ABDB(
      2100),FN(100)
       C1=1.745329E-2
       READ INPUT TAPE 2,1
       READ INPUT TAPE 2,2,(THE(I),ER(I),EI(I),VOL(I),PH(I),I=1,37)
       READ INPUT TAPE 2,12,NEXC
       READ INPUT TAPE 2,3,(PHI(J),J=1,NEXC)
       READ INPUT TAPE 2,3,(TH(J),J=1,NEXC)
       WRITE OUTPUT TAPE 3,1
       WRITE OUTPUT TAPE 3,2,(THE(I),ER(I),EI(I),VOL(I),PH(I),I=1,37)
       WRITE OUTPUT TAPE 3,4,(PHI(J),J=1,NEXC)
       WRITE OUTPUT TAPE 3,5,(TH(J),J=1,NEXC)
       IC=1
       SUMD=0.
       READ INPUT TAPE 2,12,INITRN
   100 READ INPUT TAPE 2,12,ICONT,NTOTAL
       IF(INITRN)18,18,140
   140 INITRN=INNDRN(INITRN)
       IF(ICONT)15,16,17
    15 READ INPUT TAPE 2,3,STD
       GO TO 18
    16 READ INPUT TAPE 2,3,STDV,DB
       GO TO 18
    17 READ INPUT TAPE 2,3,STD,STDV,DB
C     LOOP FOR NTOTAL
    18 DO 300 M=1,NTOTAL
       WRITE OUTPUT TAPE 3,1
       IF(INITRN)22,22,180
   180 IF(ICONT)19,20,21
    19 WRITE OUTPUT TAPE 3,11,STD
       GO TO 22
    20 WRITE OUTPUT TAPE 3,13,STDV,DB
       GO TO 22
    21 WRITE OUTPUT TAPE 3,14,STD,STDV,DB
       WRITE OUTPUT TAPE 3,9
C      LOOP FOR THETA
    22 DO 65 I=1,37
```

```
      SUMR=ER(I)
      SUMI=EI(I)
C
C     LOOP FOR OTHER NEXC EXCITORS
      DO 45 J=1,NEXC
      E2D=THE(I)+TH(J)
      IF(E2D)30,25,350
   25 I1=1
      GO TO 40
   30 E2D=360.+E2D
      GO TO 35
  350 IF(E2D-360.)35,35,37
   37 E2D=E2D-360.
   35 I1=E2D/10.+1.
      IF(INITRN)411,411,40
   40 IF(ICONT)440,411,440
  411 AN(J)=PHI(J)
      GO TO 42
  440 IF(THE(I))42,41,42
   41 FMEAN=PHI(J)
      AN(J)=FPNDRN(STD,FMEAN,INITRN)
   42 PHIT=(PH(I1)+AN(J))*C1
      IF(INITRN)441,441,420
  420 IF(ICONT)441,444,444
  441 RANV(J)=1.
      GO TO 450
  444 IF(THE(I))450,445,450
  445 RANV(J)=FPNDRN(STDV,1.,INITRN)
  450 SUMR=SUMR+VOL(I1)*COSF(PHIT)*RANV(J)
   45 SUMI=SUMI+VOL(I1)*SINF(PHIT)*RANV(J)
      SURE(I)=SUMR
      SUIM(I)=SUMI
      EV(I)=SQRTF(SUMR**2+SUMI**2)
      PHA=ATANF(SUMI/SUMR)
      IF(SUMR)50,54,60
   50 IF(SUMI)51,53,51
   51 PHA=PHA+3.14159
      GO TO 60
   53 PHA=3.14159
      GO TO 60
   54 IF(SUMI)55,56,57
   55 PHA=-1.570745
      GO TO 60
   56 PHA=0.
      GO TO 60
   57 PHA=1.570745
   60 PHAS(I)=PHA/C1
   65 CONTINUE
      IF(INITRN)680,680,650
  650 IF(ICONT)66,67,68
   66 WRITE OUTPUT TAPE 3,8,(AN(J),J=1,NEXC)
      GO TO 680
   67 WRITE OUTPUT TAPE 3,150
      WRITE OUTPUT TAPE 3,8,(RANV(J),J=1,NEXC)
      GO TO 680
   68 WRITE OUTPUT TAPE 3,8,(AN(J),J=1,NEXC)
      WRITE OUTPUT TAPE 3,150
      WRITE OUTPUT TAPE 3,8,(RANV(J),J=1,NEXC)
  680 EVMAX=EV(1)
      DO 70 I=1,37
      IF(EVMAX-EV(I))69,70,70
   69 EVMAX=EV(I)
```

TABLE A-II (Continued)

```
   70 CONTINUE
      DO 80 I=1,37
      EN(I)=EV(I)/EVMAX
   80 EDB(I)=20.*LOG10F(EN(I))
      WRITE OUTPUT TAPE 3,10
      WRITE OUTPUT TAPE 3,6,(THE(I),SURE(I),SUIM(I),EV(I),PHAS(I),EN(I),
     1EDB(I),I=1,37)
      FNUL=EN(1)
      DO 90 I=1,37
      IF(EN(I)-FNUL)85,90,90
   85 FNUL=EN(I)
   90 CONTINUE
      WRITE OUTPUT TAPE 3,156,FNUL
      FNU =1./FNUL
      SUMD=SUMD+FNU
      FN(IC)=FNU
  300 IC=IC+1
      IF(NTOTAL-1)100,100,110
  110 IC=IC-1
      FMEAN=SUMD/FLOATF(IC)
      SUT=0.
      DO 120 I=1,IC
  120 SUT=SUT+(FN(I)-FMEAN)**2
      STD=SQRTF(SUT/FLOATF(IC))
      WRITE OUTPUT TAPE 3,1
      WRITE OUTPUT TAPE 3,154
      WRITE OUTPUT TAPE 3,157,(FN(I),I=1,IC)
      WRITE OUTPUT TAPE 3,155,IC
      WRITE OUTPUT TAPE 3,160,FMEAN,STD
      SUMD=0.
      IC=1
      GO TO 100
C     FORMAT STATEMENTS
    1 FORMAT (72H
     1             )
    2 FORMAT (F5.0,5X3E16.6,F10.2)
    3 FORMAT (5F10.5)
    4 FORMAT (1H05X23HPHI CORRECTIONS (DEG) =6F10.2)
    5 FORMAT (1H05X25HTHETA CORRECTIONS (DEG) =6F10.2)
    6 FORMAT (F10.2,3E16.6,F10.2,E16.6,F10.2)
    8 FORMAT (5F10.2)
    9 FORMAT (1H010X19HRANDOM PHASE (DEG.)/5X4HNO.26X4HNO.36X4HNO.46X4HN
     10.56X4HNO.6)
   10 FORMAT (12H  THETA-DEG.3X11HSUM OF REAL5X11HSUM OF IMAG6X10HVOLT.-
     1MAG.5X5HPHASE4X11HVOL.-NORM  10X2HDB)
   11 FORMAT (1H0 7X21HSTANDARD DEV. (DEG) =F5.1)
   12 FORMAT (2I5)
   13 FORMAT (1H07X21HSTANDARD DEV. (VOL) =F10.5,15X4HDB =F6.1)
   14 FORMAT (1H07X21HSTANDARD DEV. (DEG) =F15.1//8X21HSTANDARD DEV. (VO
     1L) =F10.5,15X4HDB =F6.1)
  150 FORMAT (1H010X19HRANDOM MAGN. (VOL.)/5X4HNO.26X4HNO.36X4HNO.46X4HN
     10.56X4HNO.6)
  154 FORMAT (15X5H1/VOL)
  155 FORMAT (1H0 9X43HCALCULATING THE MEAN AND THE ST. DEV. FROM I3,18H
     1RADIATION PATTERNS)
  156 FORMAT (1H020X11HMIN (VOL) =E15.6)
  157 FORMAT (5XE15.6)
  160 FORMAT (1H010X11HMEAN (VO) =F8.3,15X20HSTANDARD DEV. (VO) =F8.3)
      END
```

TABLE A-III

RELATIVE RADIATION FIELD OF ANY NUMBER OF ELEMENTS LOCATED ANYWHERE ON A SPHERE

```
C4MR15JAN65 TOTAL RADIATION PATTERN FOR AN ARRAY OF SLOTS ON THE SPHERE
C          THE CTR. LOCATION OF THE CONE AT THETA SUB C - PHI SUB C
C      PROGRAM IS DIMENSIONED FOR A MAX. OF 6 RADIATORS (NRAD1)  AND 25
C       TOTAL RADIATION PATTERNS (NCUTS)
C  INCLUDE SUBROUTINES  DPNCOS - DDXHAN - BSUBN - FACT - ERPR
      DIMENSION HEAD(12),PI(2),SMREAT(100,6),SMIMAT(100,6),VLMAT(100,6),
     1PHAST(100,6),PSI(100),PH(100),SMREP(100,6),SMIMP(100,6),VLM(100,6)
     2,PHAS(100,6),THDET(100),ANGLE(6),PHIN(6),THN(6),PDB(50),TDB(50),BU
     3FFER(800) ,VNDBT(50),VNDBP(50),TCWR(9),PCWR(9),BCC(1),BCD(2),BCE(2
     4)
      DIMENSION TSRET(37,25),TSIMT(37,25),TVLMT(36,25),TPHT(36,25),TSREP
     1(37,25),TSIMP(37,25),TVLMP(37,25),TPHP(37,25)
      COMMON TSRET,TSIMT,TVLMT,TPHT,TSREP,TSIMP,TVLMP,TPHP,C1,PI,KEY,K1,
     1VLMAXT
C
C            TABLE OF CONSTANTS
B     PI(1) = 202622077325
B     PI(2) = 147042055061
      C1 = PI/180.
C     ----
      READ INPUT TAPE 2,1,(HEAD(I),I=1,12)
    1 FORMAT(12A6)
C     ARG = KA.....POSITIVE, LESS THAN 50. , REAL ONLY
C     THETA1 = HALF WIDTH OF CONE (DEG)
C     ALPHA = HALF WIDTH OF SLOT (DEG)
C     DTHETA = INTERVAL OF 2 PT. GAUSS INTEGRAL
C     NL = N LIMIT. POSITIVE INTERGER,=,LESS THAN 10
      READ INPUT TAPE 2,8,ARG,THETA1,ALPHA,DTHETA,NL
    8 FORMAT (4F10.6,I3)
C     CONTROL CARD TO OMIT PLOTTING ON A6.
C     NTP = 0 NO PLOT
C     NTP = 1 PGOGRAM WILL PLOT
C     NRAD1  TOTAL NUMBER OF RADIATORS ON THE SPHERE
C     ICONT = CONTROL CARD TO DETERMINE WHICH TO VARY.    0=THETA 1 =PHI
C     VOLMAX = MAX VOLTAGE ON SPHERE * IT CAN BE 0 AND PROGRAM WILL NORM
C     TO PEAK
C     NCUTS = TOTAL NUMBER OF RADIATION PATTERNS FOR ONE COMPUTAR RUN
      READ INPUT TAPE 2,111,NCUTS,NTP,NRAD1,ICONT,VOLMAX
  111 FORMAT (4I3,E15.7)
      NCU=NCUTS
      K1=0
      IC=0
      NRAD=NRAD1-1
      IF(NRAD)551,551,550
  550 READ INPUT TAPE 2,1110,(ANGLE(J),J=1,NRAD)
 1110 FORMAT (F10.5)
  551 IF(NTP)656,501,656
  656 CALL PLOTS1(BUFFER,800)
  501 IF(ICONT)513,500,513
C     NPHI = NO. OF POINTS IN PATTERN
C     NWREL = CONTROL CARD TO WRITE ELEMENT PATTERN 0=WRITE ELEMENT
C     PATTERN,= 1=DO NOT WRITE ELEMENT PATTERN
  500 READ INPUT TAPE 2,2,NWREL,PHI,THET,DT,NPHI
    2 FORMAT (I2,3F10.6,I3)
  890 XLENG=10.
      BCE(1)=6HPHI (D
      BCE(2)=6HEG) =
      BCD(1)=6HTHETA
```

TABLE A-III (Continued)

```
      BCD(2)=6H(DEG)
      BCC(1)=6H THETA
      IC=IC+1
      THDET(IC)=PHI
      IF(PHI)700,701,700
  701 PHI=1.0E-3
      GO TO 700
C     THETA= ANGLE FROM ZENITH (DEG)
C     PHIS = ANGLE AROUND THE EQUATOR OF THE SPHERE (DEG.)
C     DP   = INTERVAL IN PHI  (DEG)
  513 READ INPUT TAPE 2,2,NWREL,THETA,PHIS,DP,NPHI
  891 XLENG=5.
      BCE(1)=6HTHETA
      BCE(2)=6H(DEG)=
      BCD(1)=6H   PHI
      BCD(2)=6H (DEG)
      BCC(1)=6H   PHI
      IC=IC+1
      THDET(IC)=THETA
  700 IF(NWREL)100,657,100
  657 WRITE OUTPUT TAPE 3,10
   10 FORMAT (35H1 ELEMENT PATTERN FOR EACH RADIATOR)
      WRITE OUTPUT TAPE 3,3,ARG,THETA1,ALPHA,NL
    3 FORMAT (55H0INPUT VALUES -ARGUMENT     THETA 1     ALPHA   N LIMIT
     1/1H+60X6HDTHETA4X26HNO. OF POINTS IN FAR-FIELD//1H 12XF8.4,5XF7.2,
     25XF6.2,6XI2)
      WRITE OUTPUT TAPE 3,4,DTHETA,NPHI
    4 FORMAT (1H+60XF5.2,12XI3)
C        PROGRAM  THAT CALCULATES THE RADIATION PATTERN FOR X NO. OF
  100 DO 3101 J=1,NRAD1
      READ INPUT TAPE 2,8,TC,PC
      TCWR(J)=TC
      PCWR(J)=PC
C
C     ----
C           LOOP FOR FAR-FIELD ANGLE, THETA -P
      SIGN=1.
C     CALCULATION LOOP FOR PHI
      TCR=TC*C1
      CTC=COSF(TCR)
      STC=SINF(TCR)
      IF(ICONT)503,502,503
  502 THETA=THET
      GO TO 661
  503 PHI=PHIS
  661 IF(NWREL)504,659,504
  659 WRITE OUTPUT TAPE 3,658,TC,PC
  658 FORMAT (1H0,41HPOSITION OF RADIATORS  THETA SUB C (DEG)=F7.2,5X16H
     1PHI SUB C (DEG)=F7.2)
      WRITE OUTPUT TAPE 3,17,BCE,THDET(K1)
   17 FORMAT (1H020X2A6,F10.2)
      WRITE OUTPUT TAPE 3,660,BCC
  660 FORMAT(1H024X11HE SUB THETA,40X9HE SUB PHI//1XA6     ,4X11HSUM OF
     1REAL4X11HSUM OF IMAG,3X10HVOLT.-MAG.,3X5HPHASE,4X1H*,2X11HSUM OF R
     2EAL,4X11HSUM OF IMAG,5X10HVOLT.-MAG.,3X5HPHASE4X5H THCD3X3HPSI)
  504 DO 510 K=1,NPHI
      TR =THETA*C1
      ST =SINF(TR)
      CT =COSF(TR)
      PCP=C1*(PC-PHI)
      SPCP=SINF(PCP)
```

TABLE A-III (Continued)

```
      CPCP=COSF(ABSF(PCP))
      IF(ICONT)506,505,506
  505 PH(K)=THETA
      GO TO 507
  506 PH(K)=PHI
C     CALCULATION FOR THETA PRIME
  507 THPR=ACOSF(CTC*CT+STC*ST*CPCP)
      THCD=THPR/C1
C   CHANGING SIGN FOR E SUB PHI FIELD W
C     TEST AT 0 - 180 - 360 DEG. FOR CORRECT ANGLE PSI
      NT=THETA
      IF(PCP)760,762,762
  760 IF(PCP+PI)609,609,7612
 7612 SIG=-1.
      GO TO 6090
  762 IF(PCP-PI)609,609,7612
  609 SIG=1.
 6090 IF(NT)610,761,610
  610 IF(NT-180)5072,806,620
  620 IF(NT-360)5072,761,5072
  761 PSIR=ABSF(PI-ABSF(PCP))
      GO TO 5076
  806 PSIR=ACOSF(CPCP)
 5076 ART=SINF(PSIR)
      CPSI=COSF(PSIR)
      GO TO 5073
C     CALCULATION FOR PSI
 5072 CPSI=(CTC-CT*COSF(THPR))/(ST*SINF(THPR))
      IF(ABSF(CPSI)-1.)75,75,74
   74 IF(CPSI)741,740,740
  740 CPSI=1.
      GO TO 75
  741 CPSI=-1.
   75 PSIR=ACOSF(CPSI)
      ART=SINF(PSIR)
 5073 PSI(K)=PSIR/C1
C           LOOP TO CALCULATE SUMMATION,N=1,NL
      SUMRE = 0.
      SUMIM =0.
      DO 16 N=1,NL
C           LOOP TO CALC. BSUBN(THETA1,ALPHA,DTHETA,N,BNANS)
      CALL BSUBN(THETA1,ALPHA,DTHETA,N,BNANS)
      BSUBNA = BNANS
      ALPHAR = C1*ALPHA
      BND2AR = BSUBNA/(2.*ALPHAR)
C           CALC. 1ST DERIVITIVE OF X*H(2)SUB N*(X)
      CALL DDXHAN(ARG,N,REAL,GAMI)
C           CALC. D/DTH PSUB N(COS THETA)
      CALL DPNCOS(THCD,N,ANS)
      DPNANS = ANS
C
      ABA = ARG*BND2AR*DPNANS
      DEN = REAL**2+GAMI**2
      ABADEN = ABA/DEN
C           TEST FOR VALUE OF (J)EXP N
      NN = XMODF(N,4) + 1
      GO TO (11,12,13,14),NN
C           NUMERATOR IS REAL,POSITIVE
   11 TRMRE = REAL*ABADEN
      TRMIM = -GAMI*ABADEN
      GO TO 15
```

TABLE A-III (Continued)

```
C           NUMERATOR IS IMAGINARY,POSITIVE
   12 TRMRE = GAMI*ABADEN
      TRMIM = REAL*ABADEN
      GO TO 15
C           NUMERATOR IS REAL,NEGATIVE
   13 TRMRE = -REAL*ABADEN
      TRMIM = GAMI*ABADEN
      GO TO 15
C           NUMERATOR IS IMAGINARY,NEGATIVE
   14 TRMRE = -GAMI*ABADEN
      TRMIM = -REAL*ABADEN
   15 SUMRE = SUMRE+TRMRE
   16 SUMIM = SUMIM+TRMIM
C     TESTING FOR CORRECT SIGN ON REAL AND IMAGINARY
      IF(PCP)310,301,310
  301 IF(THETA-TC)300,305,320
  300 SUMRE=-SUMRE
      SUMIM=-SUMIM
      ERP=0.
      EIP=0.
      GO TO 315
  305 SUMRE=CPSI*SUMRE
      SUMIM=CPSI*SUMIM
      ERP=0.
      EIP=0.
      GO TO 315
  310 ERP=-ART*SUMRE*SIG
      EIP=-ART*SUMIM*SIG
      SUMIM=CPSI*SUMIM*SIGN
      SUMRE=CPSI*SUMRE*SIGN
      GO TO 315
  320 ERP=0.
      EIP=0.
      TCP18=TC+180.
      IF(THETA-TCP18)315,315,300
  315 SMREAT(K,J)=SUMRE
      SMIMAT(K,J)=SUMIM
      SMREP(K,J)=ERP
      SMIMP(K,J)=EIP
C           FIND VOLT. MAGNITUDE AND NORMALIZE TO MAXIMUM VALUE
C           CALCULATE PHASE ANGLE AND DB VALUE
      VLM(K,J)=SQRTF(ERP**2+EIP**2)
      PHAS(K,J)=ATANF(EIP/ERP)
      IF(ERP)210,240,280
  210 IF(EIP)220,230,220
  220 PHAS(K,J)=PHAS(K,J)+PI
      GO TO 280
  230 PHAS(K,J)=PI
  240 IF(EIP)250,260,270
  250 PHAS(K,J)=-PI/2.
      GO TO 280
  260 PHAS(K,J)=0.
      GO TO 280
  270 PHAS(K,J)=PI/2.
  280 VLMAT(K,J)=SQRTF(SUMRE**2+SUMIM**2)
C           CALC. PHASE ANGLE -PI/2 TO 3PI/2
      PHAST(K,J)=ATANF(SUMIM/SUMRE)
      IF(SUMRE)21,24,28
   21 IF(SUMIM)22,23,22
   22 PHAST(K,J)=PHAST(K,J)+PI
      GO TO 28
```

TABLE A-III (Continued)

```
   23 PHAST(K,J)=PI
      GO TO 28
   24 IF(SUMIM)25,26,27
   25 PHAST(K,J)=-PI/2.
      GO TO 28
   26 PHAST(K,J)=0.
      GO TO 28
   27 PHAST(K,J)=PI/2.
C     CONVERTING TO DEGREES
   28 PHAS(K,J)=PHAS(K,J)/C1
   30 PHAST(K,J)=PHAST(K,J)/C1
      IF(ICONT)509,508,509
  508 THETA=THETA+DT
      GO TO 5100
  509 PHI=PHI+DP
 5100 IF(NWREL)510,653,510
  653 WRITE OUTPUT TAPE 3,651,PH(K),SUMRE,SUMIM,VLMAT(K,J),PHAST(K,J),ER
     1P,EIP,VLM(K,J),PHAS(K,J),THCD,PSI(K)
  651 FORMAT (F7.1,3E15.7,F8.2,2X1H*,3E15.7,F6.2,F8.1,F7.1)
  510 CONTINUE
 3101 CONTINUE
      IF(NRAD1-1)663,663,6540
C     FIND MAX E AND NORMALIZE AND CONVERT TO DB FOR ONE RADIATOR
C     E SUB THETA
  663 VLEMT=VLMAT(1,1)
      DO 665 K=1,NPHI
      IF(VLEMT-VLMAT(K,1))664,664,665
  664 VLEMT=VLMAT(K,1)
  665 CONTINUE
C     E SUB PHI
      DO 668 K=1,NPHI
      IF(VLEMT-VLM(K,1))667,667,668
  667 VLEMT=VLM(K,1)
  668 CONTINUE
      DO 669 K=1,NPHI
  666 PDB(K)=20.*LOG10F(VLMAT(K,1)/VLEMT)
  669 TDB(K)=20.*LOG10F(VLM(K,1)/VLEMT)
  671 WRITE OUTPUT TAPE 3,673,BCC(1),(PH(K),PDB(K),TDB(K),K=1,NPHI)
  673 FORMAT (1H0,9X11HE SUB THETA,2X9HE SUB PHI/4XA6    ,8X2HDB9X2HDB/(F
     110.1,2F11.2))
      GO TO 801
 6540 KEY=1
C     E SUB THETA
      CALL TRADPA (PH,SMREAT,SMIMAT,VLMAT,PHAST,NPHI,NRAD,ANGLE,VOLMAX)
C     E SUB PHI
      KEY=2
      CALL TRADPA(PH,SMREP,SMIMP,VLM,PHAS,NPHI,NRAD,ANGLE,VOLMAX)
      IF(VOLMAX)800,800,8011
  800 IF(NCUTS-K1)801,801,501
 8011 K1=0
      NCU=1
  801 DO 850 L=1,NCU
      SESITT=0.
      SESITP=0.
      SSINF=0.
      IF(NRAD1-1)899,899,8010
 8010 WRITE OUTPUT TAPE 3,1,(HEAD(I),I=1,12)
      WRITE OUTPUT TAPE 3,3,ARG,THETA1,ALPHA,NL
      WRITE OUTPUT TAPE 3,4,DTHETA,NPHI
      WRITE OUTPUT TAPE 3,705,(TCWR(J),PCWR(J),J=1,NRAD1)
  705 FORMAT (22H0POSITION OF RADIATORS//5X11HTHETA SUB C3X9HPHI SUB C//
     1(4X2F12.2))
```

TABLE A-III (Continued)

```
  512 WRITE OUTPUT TAPE 3,9,BCE,THDET(L)
    9 FORMAT (1H010X11HE SUB THETA10X2A6,F7.2)
  709 WRITE OUTPUT TAPE 3,50,NRAD1,(ANGLE(I),I=1,NRAD),BCC
   50 FORMAT (1H010HTHERE ARE I1,24H RADIATORS ON THE SPHERE//20H PHASE
     1CORRECTIONS =(3F10.2)//4XA6,5X11HSUM OF REAL5X11HSUM OF IMAG6X10HV
     2OLT.-MAG.5X5HPHASE3X16HVOLT. NORMALIZED6X2HDB)
      DO 714 J=1,NPHI
      VNDBT(J)=TVLMT(J,L)/VLMAXT
      VNDBP(J)=TVLMP(J,L)/VLMAXT
      TDB(J)=20.*LOG10F(VNDBT(J))
      PDB(J)=20.*LOG10F(VNDBP(J))
      IF(ICONT)711,711,712
  711 ST=SINF(PH(J)*C1)
      GO TO 713
  712 ST=SINF(THDET(L)*C1)
  713 SSINF=SSINF+ST
      SESITT=SESITT+ST*VNDBT(J)**2
  714 SESITP=SESITP+ST*VNDBP(J)**2
      WRITE OUTPUT TAPE 3,70,(PH(J),TSRET(J,L),TSIMT(J,L),TVLMT(J,L),TPH
     1T(J,L),VNDBT(J),TDB(J),J=1,NPHI)
   70 FORMAT (F10.2,3E16.6,F10.2,E17.6,F10.2)
C     LOOP FOR E SUB PHI
      WRITE OUTPUT TAPE 3,1100,BCC
 1100 FORMAT (1H010X9HE SUB PHI//4XA6,5X11HSUM OF REAL5X11HSUM OF IMAG6X
     110HVOLT.-MAG.5X5HPHASE3X16HVOLT. NORMALIZED6X2HDB)
      WRITE OUTPUT TAPE 3,70,(PH(J),TSREP(J,L),TSIMP(J,L),TVLMP(J,L),TPH
     1P(J,L),VNDBP(J),PDB(J),J=1,NPHI)
      WRITE OUTPUT TAPE 3,1101,SSINF,SESITT,SESITP
 1101 FORMAT (1H05X16HSUM SIN(THETA) =E15.7//6X16HSUM ST*EN**2.TH=E15.7/
     1/6X16HSUM ST*EN**2 PH=E15.7)
  899 IF(NTP)901,850,901
  901 CALL AXIS1(0.,0.,2HDB,2,5.,90.,-20.,4.,0,0,1.)
      CALL AXIS1(0.,0.,BCD,-12,XLENG,0.,0.,18.,0,0,1.)
      DO 999 I=1,NPHI
      IF(ABSF(TDB(J))-20.)997,997,996
  996 TDB(J)=-20.
  997 IF(ABSF(PDB(J))-20.)999,999,998
  998 PDB(J)=-20.
  999 CONTINUE
      CALL SCLGPH (PH,TDB,NPHI,.0,0,0.,18.,-20.,4.)
      CALL SCLGPH (PH,PDB,NPHI,.1,-2,0.,18.,-20.,4.)
  894 CALL SYMBL5 (5.,5.,.15,BCE,0.,-12)
  895 CALL NUMBR1 (6.5,5.,.15,THDET(L),0.,-0)
      CALL SYMBL5 (8.3,2.05,.08,-2,0.,-1)
      CALL SYMBL5 (8.5,2.0,.1,9HE SUB PHI,0.,9)
      CALL SYMBL5 (8.5,1.75,.1,11HE SUB THETA,0.,11)
      XMOVE=XLENG+4.
      CALL PLOT1(XMOVE,0.,-3)
      END FILE 6
  850 CONTINUE
      IF(NCUTS-IC)2001,2001,501
 2001 IF(NRAD1-1)501,501,2000
C     E SUB PHI
 2000 GAIN=SSINF/SESITP
C     E SUB THETA
      GAINT=SSINF/SESITT
      WRITE OUTPUT TAPE 3,5,GAIN,GAINT
    5 FORMAT (38H1DIRECTIVITY  FOR TOTAL NO OF PATTERNS//6X9HE SUB PHI5X
     111HE SUB THETA/2E16.7)
      CALL EXIT
      END
```

TABLE A-IV

SUBROUTINES

```
CBSUBN1 SUBROUTINE TO CALC. BSUBN - INPUT - THETA1,ALPHA,DTHETA,N
C      INCLUDE DPNCOS SUBROUTINE
C                                    OUTPUT - BNANS
C            CALCULATE INTEGRAL FROM THETA1-ALPHA TO THETA1+ALPHA
C
      SUBROUTINE BSUBN(THETA1,ALPHA,DTHETA,N,BNANS)
      DIMENSION PI(1)
B     PI(1) = 202622077325
      C1 = 0.57735027
      C2 = PI/180.
      HDT = DTHETA/2.0*C2
      T = C1*HDT
      TZ = THETA1-ALPHA
      THE = TZ
      NT = 4.0*(ALPHA/DTHETA)
      SUM = 0.
      DO 20 I=1,NT,2
      TH = THE+HDT
      THETA = TH-T
      TRAD = THETA*C2
      CALL DPNCOS(THETA,N,ANS)
      SUM = SUM+ANS*SINF(TRAD)*HDT
      THETA = TH+T
      TRAD = THETA*C2
      CALL DPNCOS(THETA,N,ANS)
      SUM = SUM+ANS*SINF(TRAD)*HDT
   20 THE = THE+DTHETA
      FN = N
      TWN = 2*N
      BNANS = -(TWN+1.0)/(FN+1.)*SUM/TWN
      RETURN
      END
```

```
CDDXHAN - CALC. 1ST DERIVITIVE OF X*H(2)SUB N*(X) USING BESSEL
      SUBROUTINE DDXHAN(X,N,R,G)
      DIMENSION ANS(101),ANSN(101)
C  INPUT IS AURGUMENT (X) AND ORDER (N)
C     X CANNOT BE GREATER THAN 50.
C     N CANNOT BE GREATER THAN 100
C OUTPUT IS REAL AND IMAGINARY PARTS OF COMPLEX ANSWER
C
      PIDT = 1.5707963
      S = -1.0
      FN = N
      N1 = N+1
      N2 = N+2
      M  = N-1
C
      ARG = SQRTF(PIDT/X)
      CALL BESSEL(1,X,N,0.5,ANS,0.)
      CALL BESSEL(1,X,N1,0.5,ANSN,-0.)
C
      R = ARG*(X*ANS(N)-FN*ANS(N1))
      G = ARG*(S**M*FN*ANSN(N2)-S**N*X*ANSN(N1))
      RETURN
      END
```

TABLE A-IV (Continued)

```
CDPNCOS      DPNCOS SUBROUTINE
CDPNCOS D/DTHETA * P SUBN (COS THETA) -DOUBLE-PRECISION
C     *****************************************************************
C
C SUMMATION FROM M=0 TO M=M1
C
C          (-1)**M (2N-2M)F (N-2M) (SIN THETA) (COS THETA)**(N-1-2M)
C  SUM = - -------- -
C                              2**N (M)F (N-M)F (N-2M)F
C
C    WHERE M1=N/2 OR (N-1)/2 WHICHEVER IS AN INTERGER
C     *****************************************************************
C    DPNCOS CAN BE COMPUTED FOR N GREATER THAN 20 BY AN APPROXIMATION
C
C
      SUBROUTINE DPNCOS(T,N,A)
D     DIMENSION F(39), PI(1), THETA(1), COEFNT(20,11),FN(1)
      DIMENSION NTEST(20),N3(20,11),AB(3),F3F(3)
C           TEST SWITCH AND SET OR JUMP
      IF(ISW-12345)1,2,1
    1 ISW = 12345
      DO 100 I=1,32
D 100 F(I)=DFACT(I)
B     PI(1) = 202622077325
B     PI(2) = 147042055061
D     C1 = PI/180.
D     S = -1.0
C    FN(1)  WERE CALCULATED USING TRIPLE PRISCION ROUTINE
C    -N=17    I=1
B     FN(1)=623447446013
B     FN(2)=570014000000
D     COEFNT(17,1)=FN
C    -N=18    I=1,2
B     FN(1)=624460211013
B     FN(2)=571261777776
D     COEFNT(18,1)=FN
B     FN(1)=226447446013
B     FN(2)=173014000000
D     COEFNT(18,2)=FN
C    -N=19    I=1,2,3
B     FN(1)=625470560304
B     FN(2)=572432400000
D     COEFNT(19,1)=FN
B     FN(1)=227503221454
B     FN(2)=174035077776
D     COEFNT(19,2)=FN
B     FN(1)=630425063512
B     FN(2)=575253200000
D     COEFNT(19,3)=FN
C    -N=20   I=1,2,3,4
B     FN(1)=626500745674
B     FN(2)=573200200000
D     COEFNT(20,1)=FN
B     FN(1)=230537636335
B     FN(2)=175075637774
D     COEFNT(20,2)=FN
B     FN(1)=631503221454
B     FN(2)=576035077776
D     COEFNT(20,3)=FN
B     FN(1)=231503221454
B     FN(2)=176035100000
```

TABLE A-IV (Continued)

```
D       COEFNT(20,4)=FN
        N3(17,1)=16
        N3(18,1)=17
        N3(18,2)=15
        N3(19,1)=18
        N3(19,2)=16
        N3(19,3)=14
        N3(20,1)=19
        N3(20,2)=17
        N3(20,3)=15
        N3(20,4)=13
      2 M = N/2
        M1 = M+1
        THETA(1) = T
        THETA(2) = 0.
D       TRAD = C1*THETA
D       SINT = SINF(TRAD)
D       COST = COSF(TRAD)
C          IF N IS GREATER THAN 20 AN APPROXIMATION IS USED
        IF(N-20)20,20,15
D    15 PN=N
D       PN1=S*SQRTF(2.*PN/(PI*SINT))
D       PN2=(PN+.5)*TRAD-PI/4.
D       SUM=PN1*SINF(PN2)
        GO TO 30
C             TEST IF N DONE BEFORE
     20 IF(NTEST(N)-12345)3,7,3
C
C             CALC. TABLE OF COEF(N,I) AND N3(N,I)
      3 NTEST(N) = 12345
        NM1 = N-1
        N2 = 2*N
D       TWN = 2.0**N
        IF(N-16)32,32,33
     32 MS=0
        MT=1
        GO TO 41
     33 NNM7=N-16
        GO TO (34,36,38,40),NNM7
     34 MS=1
        MT=2
        GO TO 41
     36 MS=2
        MT=3
        GO TO 41
     38 MS=3
        MT=4
        GO TO 41
     40 MS=4
        MT=5
     41 DO 6 I=MT,M1
        MST = 2*MS
        N1 = N-MS
        N3(N,I) = NM1-MST
        N4 = N-MST
        N5 = N2-MST
D       FN4 = N4
        IF(MS)4,4,5
D     4 COEFNT(N,1) = -S**MS/TWN*F(N5)/F(N4)*FN4/F(N1)
        GO TO 6
D     5 COEFNT(N,I) = -S**MS/TWN*F(N5)/F(MS)*FN4/F(N1)*1.0/F(N4)
      6 MS = MS+1
```

TABLE A-IV (Continued)

```
C
C             CALC. SUMMATION
D    7 SUM = 0.
       DO 10 I=1,M1
       N3NI = N3(N,I)
       IF(N3NI)9,8,9
D    8 SUM = SUM + COEFNT(N,I)*SINT
       GO TO 10
D    9 SUM = SUM + COEFNT(N,I)*SINT*COST**N3NI
    10 CONTINUE
    30 A = SUM
       RETURN
       END

*INDRN
*      FAP
        COUNT    10
        ENTRY    INNDRN
INNDRN  CLA*     1,4
        ARS      18
        LBT
        ADD      =1
        ADD*     1,4
        STO*     1,4
        TRA      2,4
        END




*      FAP
        COUNT    100
        ENTRY    FPNDRN
FPNDRN  PXD      0,0
 NDRN   SXD NDRN+86,4                                                  1   AANDRN
        CLA 1,4                                                        2   AANDRN
        STA NDRN+64                                                    3   AANDRN
        CLA 2,4                                                        6   AANDRN
        STA NDRN+65                                                    5   AANDRN
        CLA      3,4
        STA NDRN+9                                                     7   AANDRN
        STA NDRN+11                                                    8   AANDRN
        STA NDRN+12                                                    9   AANDRN
        LDQ                COMPUTE RI                               0010   AANDRN
        MPY NDRN+68                                                 0011   AANDRN
        STQ                                                          *12   AANDRN
        CLA                                                          013   AANDRN
        ARS 8              COMPUTE UI                               0014   AANDRN
        ADD NDRN+69                                                 0015   AANDRN
        FAD NDRN+70                                                 0016   AANDRN
        STO NDRN+80                                                 0017   AANDRN
        LRS 35             COMPUTE VI                               0018   AANDRN
        FMP NDRN+71                                                 0019   AANDRN
        FAD NDRN+72                                                 0020   AANDRN
        SSM                                                          021   AANDRN
        FAD NDRN+72                                                 0022   AANDRN
        LRS 35                                                      0023   AANDRN
        FMP NDRN+73                                                 0024   AANDRN
```

TABLE A-IV (Continued)

```
        TSX     $LOG,4
        NOP
        LRS 35                                             0027  AANDRN
        FMP NDRN+71                                        0028  AANDRN
        STO NDRN+82                                        0029  AANDRN
        TSX     $SQRT,4
        NOP
        STO NDRN+81                                        0032  AANDRN
        LRS 35                                             0033  AANDRN
        FMP NDRN+82                                              NDRN0034
        STO NDRN+83                                        0035  AANDRN
        CLA NDRN+72                                        0036  AANDRN
        STO NDRN+84                                        0037  AANDRN
        LXA NDRN+20,4        COMPUTE NI                    0038  AANDRN
        LDQ NDRN+77,4                                      0039  AANDRN
        FMP NDRN+84,4                                      0040  AANDRN
        FAD NDRN+84                                        0041  AANDRN
        STO NDRN+84                                        0042  AANDRN
        TIX NDRN+38,4,1                                    0043  AANDRN
        CLA NDRN+77                                        0044  AANDRN
        STO NDRN+85                                        0045  AANDRN
        LXA NDRN+54,4                                      0046  AANDRN
        LDQ NDRN+80,4                                      0047  AANDRN
        FMP NDRN+83,4                                      0048  AANDRN
        FAD NDRN+85                                        0049  AANDRN
        STO NDRN+85                                        0050  AANDRN
        TIX NDRN+46,4,1                                    0051  AANDRN
        FDP NDRN+84                                        0052  AANDRN
        STQ NDRN+84                                        0053  AANDRN
        CLA NDRN+84                                        0054  AANDRN
        CHS                                                *055  AANDRN
        FAD NDRN+81                                        0056  AANDRN
        STO NDRN+85                                        0057  AANDRN
        CLA NDRN+80                                        0058  AANDRN
        FSB NDRN+73                                        0059  AANDRN
        TPL NDRN+62                                        0060  AANDRN
        CLS NDRN+85                                        0061  AANDRN
        TRA NDRN+63                                        0062  AANDRN
        CLA NDRN+85                                        0063  AANDRN
        LRS 35                                             0064  AANDRN
        FMP                                                *065  AANDRN
        FAD                                                *066  AANDRN
        LXD NDRN+86,4                                      0067  AANDRN
        TRA     4,4
        OCT 011060471625,200000000000,0                    0069  AANDRN
        DEC -2.,1.,.5,1.432788,.189269,.001308             0070  AANDRN
        DEC 2.515517,.802853,.010328                       0071  AANDRN
        BSS 7                                              *072  AANDRN
        END
*      FAP                                                       DFCT 002
        COUNT   50                                               DFCT 003
        ENTRY   DFACT                                            DFCT 004
DFACT   CLA*    1,4                                              DFCT 005
        SXA     EXIT,4                                           DFCT 006
        TMI     ERRM                                             DFCT 007
        PDX     ,4                                               DFCT 008
        TXH     ERRH,4,33                                        DFCT 009
        CLA     FAC+33,4                                         DFCT 010
        LDQ     FACL+33,4                                        DFCT 011
        STO     32767                                            DFCT 012
        STQ     32766                                            DFCT 013
```

TABLE A-IV (Continued)

```
EXIT    AXT     **,4                                                   DFCT 014
        TRA     2,4                                                    DFCT 015
FAC     OCT     373642054234,366625325502,361625325502,354642375433    DFCT 016
        OCT     347676312141,342754445564,336431360771,331515460447    DFCT 017
        OCT     324632450060,320406612232,313536270315,306747352230    DFCT 018
        OCT     302542407372,276416066357,271660127114,265553735462    DFCT 019
        OCT     261503375673,255460356735,251460356735,245504607312    DFCT 020
        OCT     241563121460,235710637400,232460425000,226672760000    DFCT 021
        OCT     223542300000,220473000000,215473000000,212550000000    DFCT 022
        OCT     207740000000,205600000000,203600000000,202400000000    DFCT 023
        OCT     201400000000,201400000000                              DFCT 024
FACL    OCT     340601645203,333527063511,326527063511,321417455031    DFCT 025
        OCT     314503647412,307436551315,303354763054,276521576726    DFCT 026
        OCT     271637541102,265075173464,260374244633,253254760330    DFCT 027
        OCT     247332706100,243440532000,236064220000,232471400000    DFCT 028
        OCT     226154000000,222300000000,216300000000,212000000000    DFCT 029
        DEC     134B8,130B8,127B8,123B8,120B8,117B8,114B8,111B8,108B8  DFCT 030
        DEC     106B8,104B8,103B8,102B8,102B8                          DFCT 031
ERRM    STZ     COM                                                    DFCT 032
        STZ     COM+1                                                  DFCT 033
        LDQ     MESMAD                                                 DFCT 034
        TRA     *+6                                                    DFCT 035
ERRH    LDQ     =0377777777777                                         DFCT 036
        STQ     COM                                                    DFCT 037
        LDQ     =0344777777777                                         DFCT 038
        STQ     COM+1                                                  DFCT 039
        LDQ     MESHAD                                                 DFCT 040
        STQ     LINK                                                   DFCT 041
        ARS     18                                                     DFCT 042
        ORA     =155B8                                                 DFCT 043
        FAD     =155B8                                                 DFCT 044
        TSX     $(ERPR),4                                              DFCT 045
LINK                                                                   DFCT 046
        PZE     EXIT                                                   DFCT 047
        CLA     COM                                                    DFCT 048
        LDQ     COM+1                                                  DFCT 049
        STO     32767                                                  DFCT 050
        STQ     32766                                                  DFCT 051
        TRA     EXIT                                                   DFCT 052
COM     OCT     ,                                                      DFCT 053
MESHAD  PZE     MESH+15,,15                                            DFCT 054
MESH    BCI   , FACTORIAL ARGUMENT EXCEEDS 33, MAX. DOUBLE-PRECISION VALUE DFCT 055
        BCI     5,OF 1.70141179E 38 RETURNED.                          DFCT 056
MESMAD  PZE     MESM+10,,10                                            DFCT 057
MESM    BCI   , FACTORIAL ARGUMENT NEGATIVE, DOUBLE-PRECISION ZERO RETURNEDDFCT 058
        END                                                            DFCT 059

*      FAP
*ERPR
        COUNT   100                                                    ERPR0002
*      ERROR PRINT OUT . VERSION USING LOWER MEMORY LOCATION FOR SIGN ON
*                                                                      ERPR0004
        ENTRY   (ERPR)                                                 ERPR0005
*                                                                      ERPR0007
*                                                                      ERPR0009
*       CALLING SEQUENCE-                                              ERPR0010
*       TSX     (ERPR),4                                               ERPR0011
*       PZE     ERRM+N,,N       ADDRESS OF ERROR MESSAGE AND NUMBER WORDSERPR0012
*       PZE     A               LOCATION WHERE INDEX 4 ON ENTRY IS STOREDERPR0013
*                               IN ADDRESS.                            ERPR0014
```

TABLE A-IV (Continued)

```
(FPTC) BOOL     117
(ERPR) SYN      *                                                      ERPR0015
*                                                                      ERPR0016
       SXA      EXIT,4                                                 ERPR0017
       SXA      EXIT+1,2                                               ERPR0018
       STO      ARG              IF IT WAS AN F TYPE FUNCTION ARG IN AC      ERPR0019
       STQ      MQ                                                     ERPR0020
       CLA      (FPTC)
       ADD      =01000000         UPDATE ERRORCOUNT WITH FORTRAN INTEGER     ERPR0022
       REM                       INSERT TEST HERE FOR ERROR LIMIT OVERFLOW  ERPR0023
       STO*     (FPTC)             FOR LATER PRINTOUT                  ERPR0024
       CLA      1,4                                                    ERPR0025
       STA      S1                                                     ERPR0026
       PDX      ,2                                                     ERPR0027
       CLA*     2,4                                                    ERPR0028
       PAX      ,4                                                     ERPR0029
       CLA      1,4                                                    ERPR0030
       STA      =15B9                                                  ERPR0031
       SUB      =15B9                                                  ERPR0032
       TNZ      *+2                                                    ERPR0033
       TXI      *-4,4,-1                                               ERPR0034
       CAL      2,4                PICK UP PZE WITH                    ERPR0035
       REM                       WITH LINKAGE DIRECTOR ADDRESS AND STATEMNTNERPR0036
       STD      LOC              STATEMENT NUMBER OR LOCATION          ERPR0037
       ANA      =077777                                                ERPR0038
       TNZ      ADD              IF IT ISENT MAIN PROGRAM FIND ADDRESS OF    ERPR0039
       CLA      AMAIN            OF WORD HAVING SYMBOLIC NAME , ELSE SET MAIERPR0040
ADD    ADD      =1                                                     ERPR0041
STA    STA      S2                                                     ERPR0042
       CAL      1,4                ALSO PICK UP TXI FOR STATEMENT NUMBER     ERPR0043
       STD      LOCEXT                                                 ERPR0044
       TSX      $(SPH),4                                               ERPR0045
       TSX      FMT1,0                                                 ERPR0046
S1     LDQ      *-*,2            WRITE MESSAGE SPECIFIED BY CALL       ERPR0047
       STR                                                             ERPR0048
       TIX      *-2,2,1                                                ERPR0049
       TSX      $(FIL),4                                               ERPR0050
       TSX      (SPH),4                                                ERPR0051
       TSX      FMT2,0                                                 ERPR0052
S2     LDQ      **                                                     ERPR0053
       STR                                                             ERPR0054
       AXT      3,4                                                    ERPR0055
       LDQ      LOCEXT+3,4                                             ERPR0056
       STR       WRITE LOCATION OR STATEMENT NUMBER                    ERPR0057
       TIX      *-2,4,1          PRINT OUT EXTERNAL,INTERNAL NO AND ARG      ERPR0058
       TSX      $(FIL),4                                               ERPR0059
EXIT   AXT      **,4                                                   ERPR0060
       AXT      **,2                                                   ERPR0061
       CLA      ARG                                                    ERPR0062
       LDQ      MQ                                                     ERPR0063
       TRA      3,4                                                    ERPR0064
       REM                                                             ERPR0065
       EJECT                                                           ERPR0066
FMT1   BCI      2,(1H0,19A6)                                           ERPR0089
FMT2   BCI      5,(16H WHEN CALLED BY A6,3H AT17                       ERPR0090
       BCI      6,,14H( INTERNAL NO.I7,6H) WITH E16.8)                 ERPR0091
AMAIN  PZE      BMAIN-1          ADDRESS OF MAIN SPECIFICATION MINUS  1      ERPR0092
BMAIN  BCI 1,*MAIN*                                                    ERPR0093
LOCEXT PZE                                                             ERPR0094
LOC    PZE      0                                                      ERPR0095
ARG    PZE                       STORAGE       FOR ARGUMENT OF ORIGINAL CALLERPR0096
MQ     PZE                                                             ERPR0097
       END                                                             ERPR0098
```

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13. ABSTRACT

The telemetry antenna used on the first two Lincoln Experimental Satellites consists of four short stubs equally spaced around, and parallel to, the spin axis of the satellite. A detailed description of the antenna and its transmission-line system is presented. Theoretical and model studies leading to the design of this antenna are discussed. Calculated and measured performance data are presented and compared.

14. KEY WORDS

LES	launching	programming
telemetry antenna	impedance	spherical antennas
transmission lines	Titan	
radiation patterns	computers	